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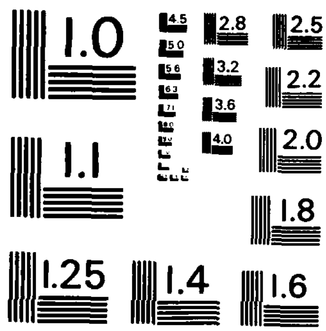

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AUTOMATION AND THE ALLOCATION OF FUNCTIONS BETWEEN HUMAN AND AUTOMATIC CONTROL: GENERAL METHOD

R. PULLIAM
H.E. PRICE

ESSEX CORPORATION

FEBRUARY 1985

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AIR FORCE AEROSPACE MEDICAL RESEARCH LABORATORY
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICES

TECHNICAL REVIEW AND APPROVAL

AFAMRL-TR-85-017

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

CHARLES BATES, JR.
Director, Human Engineering Division
Air Force Aerospace Medical Research Laboratory

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This report was prepared as a Human Engineering Data Base Supplement to the Integrated Perceptual Information for Designers (IPID) Engineering Data Compendium. It describes a general method for allocation of functions during systems development, with particular focus on what functions should be automatic. The method was originally developed for use in the nuclear power industry, and has here been redeveloped for use in aerospace systems.

The report is intended for the use of project managers, systems engineers and system designers, as an applied guide during the development of aerospace systems. It provides a detailed procedure for allocation of functions (AOF), a procedure to be applied during the research, development, test and evaluation (RDT&E) process. The report uses a hierarchical structure in which each of five sections treats the AOF process at an increasing level of detail, as follows: Section 1 concerns how to use the report. Section 2 describes (Cont.)

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Requirements Analysis	Test and Evaluation	Control Models
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Engineering Design	Man-Machine Models	Role of Man
Inductive Logic	Theory of Design	Life-Cycle Cost
Control Systems	Design Hypothesis	Automation
Deductive Logic	Human Performance	Cognitive Models
Human Factors	Human Engineering	

19. Abstract (Continued)

the RDT&E process in terms of the cyclic decision and test steps by which design proceeds, and identifies those steps which are critical to a successful AOF. Section 3 focuses on one critical step in RDT&E, the formation of design hypotheses, and describes that step in greater detail. Section 4 focuses even more narrowly on a step within design hypothesis, and identifies four sets of criteria which should be applied in sequence to assist AOF decisions. Finally, Section 5 identifies human-machine models by which aerospace systems can be analyzed during systems design.

In each of these sections the focus is on the allocation of control functions to human operators or to automation. Nevertheless the procedure and logic of the report will apply to the more general problem of allocating system functions between humans and machines. An appendix is provided which lists typical functions which are performed well or poorly, by humans and by automation.

PREFACE

This report was prepared as a supplement to the Engineering Data Compendium being developed under the Integrated Perceptual Information for Designers (IPID) project. IPID is concerned with the consolidation and technical presentation of perceptual and human performance data to enable their use as an effective resource by designers of simulators and operational displays and controls. It is a multi-agency effort supported by the Air Force, Army, Navy and NASA and is managed by the Air Force Aerospace Medical Research Laboratory at Wright-Patterson AFB.

The pertinent research literature contains a staggering volume of potentially valuable human performance data and principles that have not been systematically considered for systems design. Early in the IPID project, the domains of sensation, perception, human information processing and performance were reviewed with respect to their potential value to control and information display design. Forty-five technical subareas were then selected for detailed treatment in a Handbook of Perception and Human Performance. These subareas were authored by some 65 recognized subject-matter experts. The handbook is to be published in early 1986 by John Wiley and Sons as a two-volume work of approximately 3000 pages. The information in the Handbook was organized so that it would be amenable to distillation into specialized data abstracts or entries for consolidation into an Engineering Data Compendium. The emphasis of the Compendium is on a usable presentation of behavioral data to design engineers.

In addition to the basic research topics covered by the Handbook, the following areas of investigation were reviewed by subject-matter experts to identify useful data for extending the range of the Compendium to the applied research domains:

- Information coding, portrayal and format
- Target detection, recognition and identification
- Automation and allocation of functions
- Person-computer dialogue
- Feedback, warning and attentional directors
- Human performance reliability
- Controls
- Vibration and visual displays

This report on Automation and the Allocation of Functions has been produced as a separate volume from the Compendium to enable its early dissemination to systems designers. Timeliness seemed especially critical given the rapidly changing state of knowledge and technology in this domain.

This report describes a general method for allocating functions during systems development, with particular focus on what functions should be automatic. The method was developed originally for the design of controls in the nuclear power industry; here it has been redeveloped for aerospace systems. As described, the method applies broadly to allocation of functions during systems acquisition, and to both control and non-control functions, but particular attention is given to the allocation of control functions between humans and automation (machines).

This method combines the best features of methods reported earlier, with improvements to make it more practical and broadly useful. The method includes three special features. First, it provides for a systematic interaction of hypothesis and test at all stages of development. Second, it embeds the allocation logic within the systems design process, and relates allocation decisions to other decisions of design. Finally, it provides a more thorough treatment of human perceptual and cognitive function, in contrast to the focus on psychomotor issues which has dominated prior methods. Despite these improvements the allocation of functions is, and will remain, an intractable problem in system design. This method will not provide an ultimate solution. It is offered as one more step toward the common goal of engineers and engineering psychologists: the design of systems in which humans and machines will work together with optimal effectiveness and satisfaction, serving human needs by a symbiosis of human and machine capabilities.

This report is meant as a user document, and not a report of original research. The research was reported by the authors in earlier publications, which are cited as references. Earlier research was supported by the USAEC under Oak Ridge National Laboratory Subcontract No. 9027, and Department of Energy Interagency Agreement No. 40-550-75.

This work was performed by Essex Corporation through a contract with MacAulay-Brown, Inc. under Air Force prime contract F33615-82-C-0513. Dr. Kenneth R. Boff was the Air Force Aerospace Medical Research Laboratory Program Manager. Mr. Gian Cacioppo was the Program Manager with principal support by Ms. Judy Williams for MacAulay-Brown, Inc. The Essex Corporation Program Manager was Mr. Clarence A. Semple. Dr. Robert Pulliam was the Essex Principal Investigator for this project.

This work was accomplished under AFAMRL Human Engineering Division Project 7184, Task 26, Work Unit 06. The Program is grateful to Mr. Charles Bates, Jr., HE Division Chief and to Dr. Thomas Furness III, Branch Chief, for their support. This effort was partially supported by funds from the Air Force Deputy for Simulators, ASD/YW. We are indebted for this sponsorship to Mr. Art Doty and Mr. Jim Basinger, ASD/YWE, and Mr. George Dickison and Ms. Nancy Droz, ASD/YWB. Ms. Gloria Calhoun, AFAMRL/HEA, and Dr. Janet Lincoln, New York University, made vital contributions to the success of this effort during its initial phases. Dr. Hershel Self, AFAMRL/HEA, carefully reviewed and commented on the manuscript. Administrative assistance was provided by Tanya Ellifritt, AFAMRL/HEA.

The authors must acknowledge their debt to others, without whom this work could not have been achieved. Among these are Mr. James Bongarra and Dr. Charles Sawyer, who are coauthors of the original research. Dr. H. P. Van Cott directed portions of the historical research, and has been a constant advisor. Finally, we appreciate the personal support of Mr. Clarence A. Semple, who directed this project and made possible its completion under exceptionally difficult circumstances.

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LIST OF EXHIBITS

SUMMARY

This report describes a general method for allocation of functions during systems development, with particular focus on what functions should be automatic. The method was originally developed for use in the nuclear power industry, and has here been redeveloped for use in aerospace systems, and in conjunction with data of the USAF Human Engineering Data Base.

The report is intended for the use of project managers, systems engineers and system designers, as an applied guide during the development of aerospace systems. It provides a detailed procedure for allocation of functions (AOF), a procedure to be applied during the research, development, test and evaluation (RDT&E) process. The report uses a hierarchical structure in which each of five sections treats the AOF process at an increasing level of detail, as follows: Section 1 concerns how to use the report. Section 2 describes the RDT&E process in terms of the cyclic decision and test steps by which design proceeds, and identifies those steps which are critical to a successful AOF. Section 3 focuses on one critical step in RDT&E, the formation of design hypotheses, and describes that step in greater detail. Section 4 focuses even more narrowly on a step within design hypothesis, and identifies four sets of criteria which should be applied in sequence to assist AOF decisions. Finally, Section 5 identifies human-machine models by which aerospace systems can be analyzed during systems design.

In each of these sections the focus is on the allocation of control functions to human operators or to automation. Nevertheless the procedure and logic of the report will apply to the more general problem of allocating system functions between humans and machines. An appendix is provided which lists typical functions which are performed well or poorly, by humans and by automation.

GLOSSARY OF TERMS AND ABBREVIATIONS

Accessory functions. Functions which are not required in normal operation of the system. See Section 1.

AOF. Allocation of Functions (abbrev.)

Allocation. When used alone, to be read as "allocation of functions to humans or to machines."

AOF hypothesis. One of the three design hypotheses: Engineering, AOF, Human Factors. The AOF hypothesis defines the human-machine interface. See Subsection 3.2.

AOF solution. One of the three elements of the design solution: Engineering, AOF, human factors. When an AOF hypothesis meets T&E criteria, it can be considered an AOF solution.

Analogy. See Analogous technology.

Analogous technology. The intellectual base materials, based on past technologies, from which all invention proceeds. See Section 3.0.

Analysis phase. Of the systems development process, the steps early in design during which the future system is analyzed without formulating specific engineering details. Roughly equivalent to the "functional design phase."

Automation. The mechanization of human control tasks. In this report the terms "machine" and "automation" are used similarly in the phrase "allocation of functions to humans or machine/automation." The term used will be the term which seems most appropriate for the context, but in general the procedures for allocating functions to machines are equivalent to those for allocating functions to automation.

Balance of value AOF. The primary criterion by which AOF is decided: whether automation or humans can best perform the function. Not as simple as it sounds. See Subsection 4.2.

Buyers. Those who contract for acquisition of a system. They may, or may not be the users.

C^3I. Command, control, communication and intelligence. (also used in the literature are C^3, C^2, other abbreviations).

Cognitive support. Meeting a specialized human requirement for information. See subsection 4.4.

Control functions. Those functions required to control the system. See Introduction.

Decomposition. The subdivision of a design concept into achievable parts. A step in the design cycle. See subsection 2.2.

Deductive testing. Testing by intellectual analysis; contrasted to empirical testing.

Delta. The R&D requirement; what has to be invented or developed. The difference between existing technology and what is to be achieved by design.

Design decision cycle. The design decision logic, with feedback and iteration added.

Design decision logic. The underlying intellectual process by which all design must occur.

Design decision process. The practical procedure by which design of a large system must be organized.

Design documentation base. The central records of a design activity.

Design hypothesis. The three steps of invention, taken together: Engineering hypothesis, AOF hypothesis, human factors hypothesis. See Section 3.0.

Display functions. Functions required to display system information to operators and decision makers.

Documentation. (1) Job documentation: Procedures, check lists, automated procedure displays. (2) Engineering documentation: The design documentation base.

Embedded training. Instructional program embedded in an operational computer system.

Empirical testing. Practical testing by applying elements of the system in actual or simulated use. Contrasted to deductive testing.

Engineering concept. The preliminary assumption that a new technology can meet a user requirement. Part of the requirements statement. See subsection 2.1 and paragraph 3.1.2.

Engineering solution. One of three elements of the design solution: Engineering, AOF, human factors. When an engineering hypothesis meets T&E criteria, it becomes an engineering solution.

End-users. Those whose needs the system is intended to meet. Not necessarily the sponsors of the system.

Engineering hypothesis. One of three elements of the design hypothesis: Engineering, AOF, human factors. The step by which a provisional engineering design is invented. See subsection 3.1.

Engineering concept. The general preliminary assumption concerning technology for a new system. See paragraph 2.1.2.3.

Engineering subsystem. Any system can be defined as consisting of an engineering and a human subsystem; AOF defines the boundary between those subsystems.

Function. A conceptual element of a system, with inputs, process and outputs. See Section 1.

Functional design. A conventional term for early steps in design, during which functions are defined. See critique of this concept at paragraph 2.5.6.

HF. Human factors (abbrev.).

HF solution. One of three elements of the design solution: Engineering, AOF, human factors. When a HF hypothesis meets T&E criteria, it becomes a HF solution.

Hardware concept. Provisional hardware design, stated in functional terms. See paragraph 3.1.4.

Heuristic. Exploratory method of solution.

Human factors hypothesis. One of three elements of the design hypothesis: Engineering, AOF, human factors. The step in which a provisional human organization is invented. See subsection 3.3.

Human engineering. As a generic term, equivalent to human factors engineering. More specifically, can mean just the study of physiology in relation to human work.

Human factors engineering. A discipline concerned with the design of manned systems. It includes consideration of elements such as conventional human-machine interface design, applied cognitive science, and the development of human support structures: training, selection, job design, career progression, job procedures, etc.

Human-machine interface. More commonly: man-machine interface. Defined by the allocation of functions. See paragraph 2.3.2.

Human subsystem. A system can be defined as consisting of an engineering and a human subsystem; AOF defines the boundary between those subsystems. See Section 1.

Hypothesis. (1) An intellectual step taken during the process of design. (2) The formalization of such steps in design procedure. (3) Equivalent to "invention," prior to confirmation by tests. (4) Inductive logic in design.

Informational function. A function which defines a required flow of information within a human-machine system. See Section 1.

Iteration. One kind of feedback in the design decision cycle. Iteration includes both feedback to correct deficiencies, and a repetition of steps to generate greater levels of detail. See subsection 2.5.

Job documentation. Equivalent to "procedures." Not documentation as stored in the design documentation base.

Life cycle systems management. The concept of designing a system, and forecasting costs, for the life of the system from concept to disposal.

Machine. See "automation."

Material function. A function which defines a requirement for physical hardware in the system. Contrasted to "informational function." See Section 1.

Model. As used in Section 5: A representation of human and equipment relationships, expressed principally as a graphic diagram.

Necessary functions. Functions required to achieve minimal normal system operation. Contrasted to "accessory functions." See Section 1.

Organizational design. The design of an organization into which the principal operators and users of a system can fit. Includes elements such as job design, a management and supervisory structure, personnel, payroll, etc.

Procedures. (1) The materials provided to guide humans in a work or operational sequence: Written documents, check lists, automated or embedded procedures, maintenance documentation. (2) The operating sequences themselves.

Provisional functions. Functions which have been hypothesized, but not validated by the design cycle.

R & D. Research and development (abbrev.).

RDT&E. Research, development, test and evaluation (abbrev.). The conventional expression for steps in system development as formalized by the systems approach to design.

Requirement. The original statement of need for a new system. See paragraph 2.1.2.

Roles. Sets of provisional human and machine tasks, stated in functional terms. "Roles" evolve into "tasks" as the design approaches completion. See paragraph 3.2.1.

Role of man. A statement of how, in general, humans are to be used in the new system. A part of the requirements statement.

Software concept. Provisional software, stated in functional terms. See paragraph 3.1.4.

Sponsors. Those who establish the requirement and secure funding for development of a system.

State transitions. Of a system and the states it can assume, the process of going from state to state. Of an aircraft - flying, ground operations are states; takeoff is a state transition. State transitions create a major requirement for control functions.

Systems approach. The modern "whole system" approach to design. Not just the hardware, but the human subsystem, support and logistics, all deliverable at a time certain to form an operational capability.

System users. End users, commanders, operators, maintenance and support personnel.

T & E. Test and evaluation (abbrev.). Uses deductive tests, empirical tests and evaluation against criteria. See subsection 2.4.

Tasks. Specific actions performed in the end system by humans or machines. "Tasks" emerge from the more broadly defined "roles," as the design nears completion. See paragraph 3.2.1.

Technical opportunity. The perceived future capability to which a design responds. See paragraph 2.1.2.3.

Users. See "end-users" and "system users."

Utilitarian considerations. The consideration that if a human is present, paid for and not otherwise occupied, he or she should be considered to perform a function, even though automation might otherwise be the preferred solution. See subsection 4.3.

INTRODUCTION

HOW TO USE THIS REPORT

This Technical Report supports the USAF Human Engineering Data Base (HEDB) by offering a general method for the allocation of system functions to human or automatic control. It can be used by project managers, system analysts, and system designers to assist in determining the allocation of functions during systems development, and should be used in connection with data from the HEDB. Sections which follow describe a procedure for allocation of functions (AOF), a procedure which is closely linked to other elements of the design decision process, and of the research, development, test and evaluation (RDT&E) cycle. Although the focus is on automation versus human control, this procedure will apply to the more general question of allocating all functions between humans and machines during systems design.

ORGANIZATION OF THE REPORT

This report contains five numbered sections, each of which treats a major aspect of the AOF process as part of an overall design decision logic. These five sections are in turn divided into decimally numbered subsections, each of which describes a discrete decision step, a decision criterion, or an analytic tool. Section 1 is a summary; Sections 2 through 4 are hierarchical, in that they describe the design process, and each subsequent section expands in detail on a part of the preceding section. Section 5 provides tools for analysis. This organization is represented by Exhibit I, which shows the logical subordination of subsections, and which can be used as a graphic table of contents. These contents are described below:

Section 1 - Allocation of Functions

This section defines the problem of allocation of functions, defines key terms used, and summarizes the method which later sections will describe in detail.

Section 2 - Decision Logic in Design

This section describes how allocation decisions are embedded in the systems design cycle. The systems development process is explained in terms of the iterative, logical steps which a systems team must take at every phase of analysis and design. These steps include both invention and test, and must be reiterated to correct errors and to develop increasing levels of detail.

Each of the five included steps is represented by a decimally numbered subsection, numbers 2.1 through 2.5. Subsection 2.1, PREPARATION, details critical preliminary actions. It is followed by subsection 2.2, IDENTIFYING FUNCTIONS, which details how the design concept is partitioned into functions, and how functions may be recognized. Subsection 2.3, DESIGN HYPOTHESIS, explains how a set of hypotheses is formulated (or "invented"), concerning how each function might be accomplished by people or by machines. Subsection 2.4, TEST AND EVALUATION, describes how these hypotheses are tested, either analytically or empirically. Finally subsection 2.5, ITERATION, explains the reiteration by which hypotheses are corrected, aligned with each other, and decomposed into smaller functions until the design is completed in detail.

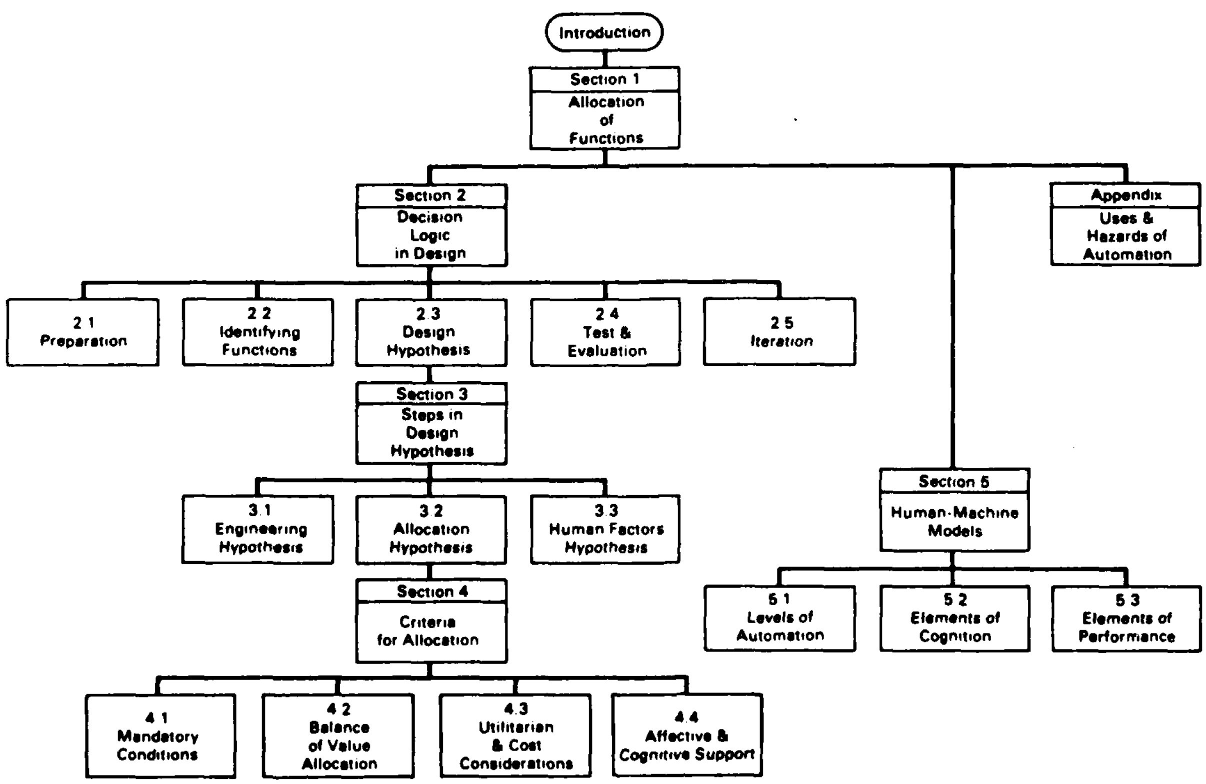
Section 3 - Steps in the Design Hypothesis

This section is shown as subordinate to step 2.3 of the prior section, and expands on the design hypothesis. This is the critical inventive step in design, and must be examined in detail. During this step a hypothetical design solution is invented for each previously defined function. Invention consists of three interrelated hypotheses, each of which is described in a numbered subsection. Subsection 3.1 treats the ENGINEERING HYPOTHESIS, subsection 3.2 the ALLOCATION HYPOTHESIS, and subsection 3.3 the HUMAN FACTORS HYPOTHESIS. These three steps are interactive, and are repeated until three hypotheses are found which are mutually compatible.

Section 4 - Criteria for Allocation

This section is shown as subordinate to subsection 3.2, since it supports that step by identifying four criteria for the allocation hypothesis.

Exhibit I
Organization Of The Report



Subsection 4.1, MANDATORY CONDITIONS, identifies cases in which there is a clear and mandatory choice between human and machine control. Subsection 4.2, BALANCE OF VALUE ALLOCATION, explains how the relative suitability of humans versus automation can be weighed in non-mandatory cases. Subsection 4.3, UTILITARIAN AND COST CONSIDERATIONS, explains how human utility and comparative costs are taken into account. Finally Subsection 4.4, AFFECTIVE AND COGNITIVE SUPPORT, identifies the purely human needs which must be considered before an allocation decision can be final.

Section 5 - Human-Machine Models

This section explains how diagrammatic models of human-machine interaction can be used as tools of analysis and design. Subsection 5.1, LEVELS OF AUTOMATION, explores several configurations of humans in relation to controls. Subsection 5.2, ELEMENTS OF COGNITION, shows how models can help to identify the cognitive and perceptual limits of a human operator. Subsection 5.3, ELEMENTS OF PERFORMANCE, broadens the issue to include psychomotor performance and the effects of social and affective settings.

Appendix - Uses and Hazards of Automation

The report closes with a comparative list of cases. Several authors have published lists, showing tasks which are better performed by humans, contrasted with tasks better performed by machines. This appendix offers four such lists, summarizing the literature on that subject. They can be used as a verifying reference, to determine whether an allocation made using the logic of Sections 1 through 5 is consistent with conventional rules of thumb.

USE OF TERMS

For convenience, the abbreviation "AOF" or the noun "allocation" will be used in sections which follow, and will always represent the full phrase "allocation of functions between humans and automation."

SECTION 1

ALLOCATION OF FUNCTIONS

This section introduces the problem of allocation of functions (AOF), and the design decision process within which AOF occurs. Included will be the definition of certain key terms.

THE PROBLEM

In most aerospace systems there is a close sharing of tasks between humans and machines. How these tasks are apportioned is determined by the design of the system - the physical equipment, and the human organization; we call that apportionment the "allocation of functions between humans and machines." It is one of the most basic of system design decisions. Most AOF choices are made during the analysis and early design phases, and they strongly determine how well humans and machines can work together in performing the system mission.

Traditionally, AOF decisions have been made intuitively, not as deliberate steps in design. It was only with the development of systems theory that AOF was formally recognized, and even now it is often given only perfunctory attention. This is in part because there is as yet no accepted and reliable procedure for AOF. The objective of this report is to provide such a procedure, making use of data from the HEDB. Using this procedure will ensure that AOF decisions are made systematically, and at appropriate points during systems design. It will assure that decisions are based on appropriate criteria, that they are made in interaction with related decisions of human and engineering design, and that they are clearly documented so that they will appropriately affect decisions made later in the design process.

THE ENGINEERING AND HUMAN SUBSYSTEMS

Whether or not they are systematically decided, the functions of a system are allocated between two major subsystems - the hardware, or engineering subsystem, and the human organization, or human subsystem. The engineering subsystem includes the major mission-performing components of a system plus all needed ground support, facilities and logistics hardware. The human subsystem includes the human organization, plus the selection, training, procedure development and other utilities which give the organization direction, structure, and informational support.

To design these two subsystems requires two highly divergent kinds of professional skill. The engineering subsystem is developed by teams from the engineering disciplines, and the human subsystem by teams from the human factors disciplines. Allocation of functions requires both kinds of expertise, and it will be successful only to the extent that those two teams remain in close communication. This communication cannot be limited to a "functional analysis" phase. There is no such single phase in design. AOF is a continuing process which requires the interaction of engineering and human factors disciplines, from the earliest concept development and throughout the RDT&E process, for the life of the system.

WHAT IS A "FUNCTION"?

In design engineering, a function is a thing or event that is needed to achieve the mission. The concept of "functions" recognizes that any future system can be conceived in terms of a set of subprocesses, defined so far as possible in the abstract, and in terms of input and output products. These abstractions provide the tools for thinking about the system during the concept phase, and before any hardware or human organization exists. Thinking in functional terms permits the design team to plan the elements which might compose a new system without deciding exactly how those elements will be built. A function has at least the following characteristics:

A Function Provides an Interim Product

Each function produces an interim or subsystem product, and can be defined by its inputs, outputs and constraints. The products of a function can be either material or informational. "Produce thrust" and "lower landing gear" are material functions: "display velocity" and "plan landing" are informational. Informational functions are often overlooked or inadequately defined during functional analysis.

Categories of Functions

The functions of a system may be either necessary or accessory.* Necessary functions are required for mission success. Failure of a necessary function results in mission failure. Accessory functions provide alternate paths to accomplishment, or add capabilities which are desirable but not critically required. In an automobile, "propulsion," "steering" and "speed control" are necessary, while "wipe windshield" and "provide spare tire" are accessory functions. Some authorities identify control functions as a separate category, contrasted to dynamic functions. While control functions should be separately identified, they are themselves always either necessary or accessory, and should be so classified to aid in tradeoff studies. Display (or instrument) functions and affector functions are the subsets of control functions. Exhibit 1 (next page) suggests these relationships.

There Are Many "Right" Sets of Functions

There are many possible ways to conceive a future system, and even more ways to decompose one into functions. There is no one "correct" functional design. Some are better than others, but this will change with any change in criteria or advance in technology. The designer's task is to discover, from among millions of possible functional designs, one set of functions which approaches the optimum, and which can be achieved within the

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* Alternative terms appear in the literature. These include "basic or secondary" (Demarle and Shillito, 1982), and "additive or multiplicative" (Price, Smith and Behan, 1964).

available resources.

Humans or Machines?

The central question is whether each function will be performed by humans or machines. At first there appear to be three options: allocate to humans, to machines, or to a combination of the two acting together. At the major subsystem level, most functions normally must be allocated to some combination of people and machines. But these major level functions must then be decomposed by partition into second-, third-, and nth-level functions. Ultimately a level of system decomposition will be reached at which each function is allocated wholly to humans or wholly to machines.

"Keeping the Solutions at Bay"

Although each function is an abstraction, it is necessarily based on the designer's experience with real machines and real people, and each function must be defined so that it can be achieved with real technology. Should we try to analyze functions as pure abstractions? Some experts say yes. They emphasize that analysts should abstain from any assumption about how a function might be accomplished in the real system. Keep the conception abstract, they say, to keep your options open and to avoid any predisposition toward past, conventional solutions. The designers should, they say, "keep the solutions at bay" until a functional design is complete.

In general this is good advice. Functions should be defined in terms of their inputs, outputs, requirements and constraints - not in terms of assumed machine components or human organizations. The designers should look for new and better solutions, not familiar ones. Such an attitude is desirable, but as an absolute it is unrealistic. Real world design, and in fact all human

Exhibit 1
Categories Of Function

Categories	Subcategories		
	Dynamic	Control	
		Affector	Display
Necessary	Propel Vehicle	Control Speed	Display Speed
Accessory	Defog Rear Window	Turn Defog Off/On	Display Defog "On" Light

Necessary functions are those within the minimum set required for completing the mission under optimal conditions. All other functions are accessory. Within those categories, functions may be further categorized as dynamic or control. Control functions may be further categorized as control affector and display functions. Examples of typical automobile functions are displayed in cells of the table.

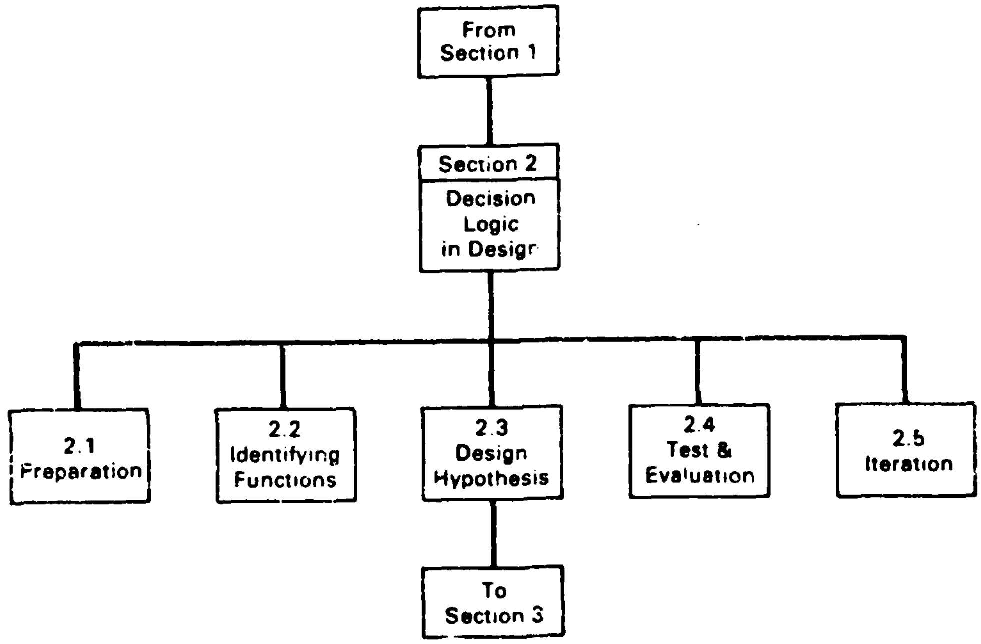
invention, occurs by adaptation. It is inevitable, and actually useful, that as each function is defined the designers will begin to think about how it can be realized with real technology. In the sections which follow, we will explain how functions are actually defined by interaction among concrete design hypotheses.

SECTION 2

DECISION LOGIC IN DESIGN

This section describes how allocation of functions (AOF) decisions are embedded in other design activities, and in the normal cycle of design decision logic. It will first describe the theory of design, and will then suggest five procedural steps by which a good AOF can be achieved. Exhibit 2A is an extract of the original introductory exhibit (Exhibit I), showing those five steps and the subsections in which they are treated.

Exhibit 2A
Five Steps of Design Decision Logic
(From Exhibit I)



THE THEORY OF DESIGN - HYPOTHESIS AND TEST

Design occurs as an iterative logical cycle which includes alternating steps of hypothesis and test. Exhibit 2B suggests this relationship. Step 1 represents an incompletely developed state of design at a given time S(t). Step 2 is the inventive step in which the designer hypothesizes a way to achieve some element of the design. This hypothesis is then subjected to empirical or analytic tests in step 3, to determine whether it meets criteria and is consistent with other elements of the design. Most hypotheses are not immediately acceptable, and must be modified or reconsidered (step 4) by feedback to the hypothesis step. When a hypothesis is acceptable it becomes an element of the developing design in step 5. Step 6 shows that the design then advances to a more fully developed state S(t+1).

Exhibit 2B
Theory Of Design – Hypothesis And Test

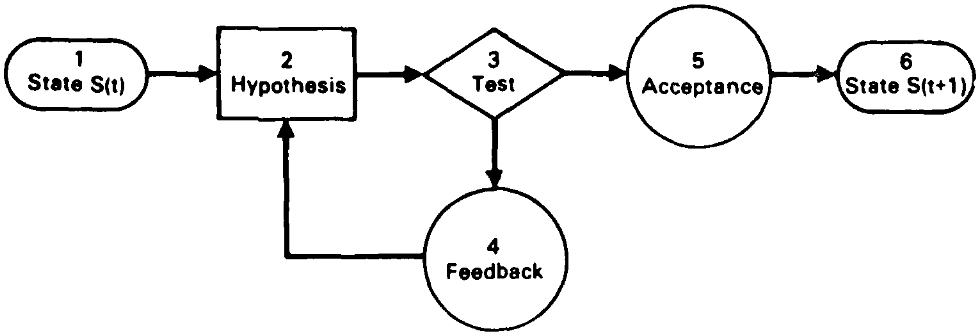


Exhibit 2C compares the roles of hypothesis and test. These cyclic steps occur first very rapidly within the minds of designers, and then more deliberately as steps of synthesis and evaluation within the design team. Finally they are formalized in the cycles of development and test required by RDT&E regulations. These cycles perform the following functions:

o They permit inductive logic, experience, intuition and art to be applied to requirements, and then to be checked by deductive logic.

o They permit the design to be decomposed into manageable elements or functions for initial solution, and then to be tested as an integrated system.

o They permit a design to evolve from a set of abstract major functions toward concrete engineering details.

o They permit continuous testing of the developing design.

Exhibit 2C
Characteristics Of The Hypotheses And Test Steps In Design

Characteristic	Step	
	Hypothesis	Test
Process	Invention Synthesis Decomposition	Measurement/Analysis Evaluation Integration
Treatment	Tentative Creative	Confirmatory Critical
Logic	Inductive	Deductive

THE PRACTICE OF DESIGN - A FIVE-STEP PROCEDURE

To this point we have considered theory. Now we will describe five procedural steps which apply that theory, and which are included in all good design practice. First we will summarize these five steps and then subsections 2.1 through 2.5 will treat them in detail. Refer to Exhibit 2D:

- o Preparation. This step (detailed in Subsection 2.1) ensures that the necessary organization and information are in place before design begins. It provides for specialist teams, specification of mission requirements, definition of the role of man, and a design data base.

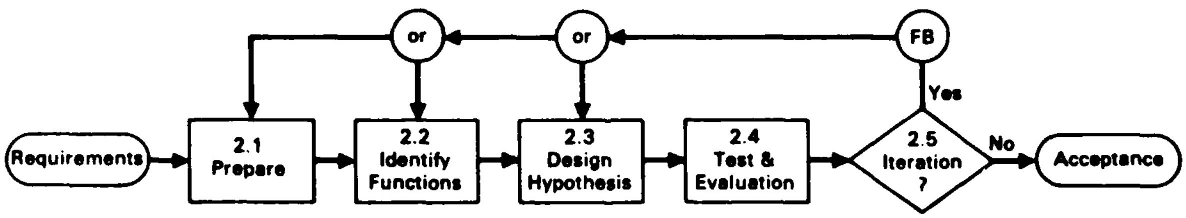
- o Identifying Functions. This step (Subsection 2.2) provides for decomposition of the future system into functions, first at a gross level, and then with increasing fineness of detail.

- o Design Hypothesis. In this step (Subsection 2.3) a design hypothesis is proposed for each function.

- o Test and Evaluation. This step (Subsection 2.4) subjects each function to deductive, simulation and empirical tests, first as individual functions and then as elements of an integrated design.

- o Iteration. This step (Subsection 2.5) uses findings of the test step to control feedback, in order to change the direction of design, to refine hypotheses, and to generate finer levels of detail. This feedback results in a cyclic repetition of steps 2.1 - 2.5 until the design is complete.

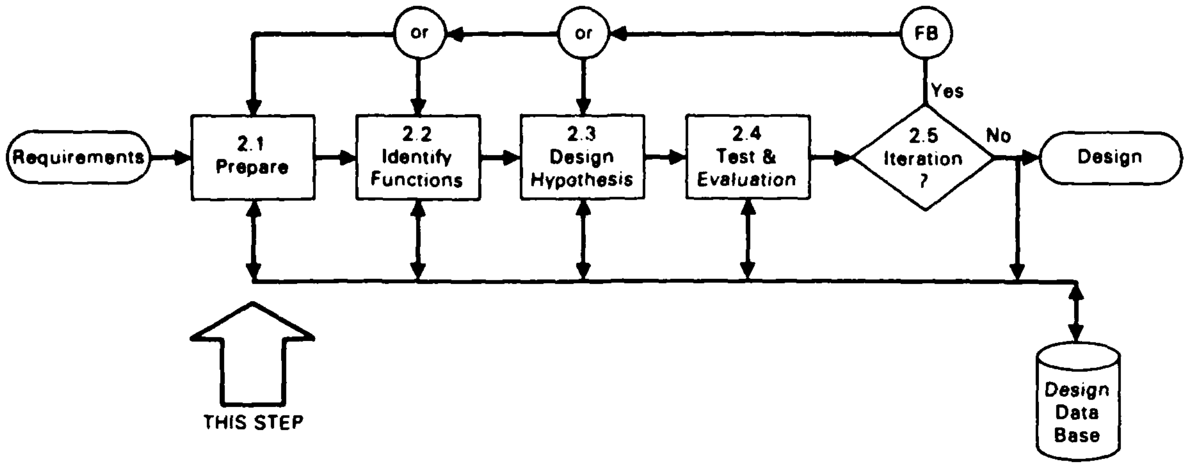
Exhibit 2D
The Design Decision Cycle (Simplified)



2.1 PREPARATION FOR DESIGN

This is step 2.1 of the design decision cycle, as illustrated by Exhibit 2.1A. Exhibit 2.1B shows the step in expanded form, including three major actions described by paragraphs 2.1.1 through 2.1.3, following.

Exhibit 2.1A
The Design Decision Cycle – Step 2.1



2.1.1 <u>Organize for Design</u>

Large systems are designed by the interaction of specialist teams, and the allocation of functions depends on their coordination. Coordination results first from central management, second from interteam communications, and finally from an interdisciplinary composition of teams and committees. Here we are particularly concerned that human factors disciplines will take part in decisions which affect AOF. To achieve a favorable organization for design, the following should be considered:

o <u>Identify Leaders</u>. Identify a project director or lead engineer, and leaders of specialist teams. Specify who will be responsible for interteam coordination, and for resolving conflicts.

o <u>Identify Discipline Requirements</u>. Identify the professional skills required, and specify required levels of experience. Include persons with competence in human engineering, organizational design, training and procedure development.

o <u>Plan for Continuity</u>. Identify key people who will remain with each team through several phases of design. The composition of teams must change, but continuity is necessary to good design.

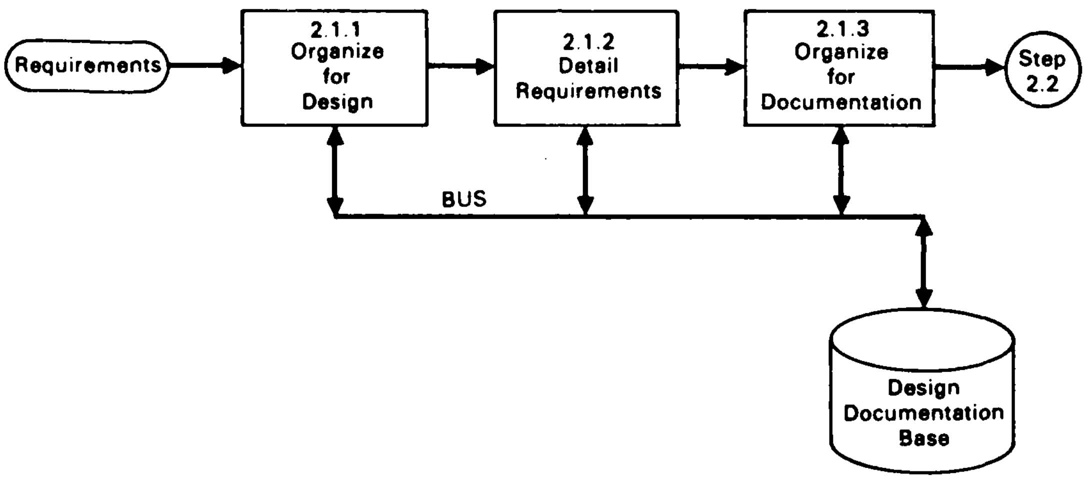
o <u>Specify Consultation</u>. Specify requirements for interteam consultation. Plan coordination and schedules. If several contractors are involved, require contractor-to-contractor coordination and documented agreements.

o <u>Include System Users</u>. Include experienced users. Persons with hands-on experience as users of analogous systems can provide judgments concerning the practicality of design. "Users" should include the end-users, those who will operate the system, plus builders, commanders, pilots, operators, maintainers and supporters.

2.1.2 Detail Requirements

This is the second action shown by Exhibit 2.1B, and it includes four subordinate steps as illustrated by Exhibit 2.1C. These steps ensure a clear understanding among the system developers, the buyers or sponsors, and the end-users of the future system. The buyers are a contracting office. The sponsors are those responsible for acquisition, in the Air Force typically a major air command. The sponsors may or may not be the end-users. For instance, a ground combat support system might be sponsored by Air Force Systems Command, but its end-users would be soldiers on the ground. The following steps will ensure that the requirements statement is complete, that it represents the intention of the sponsors, and serves the needs of end-users.

Exhibit 2.1B
Preparation For Design



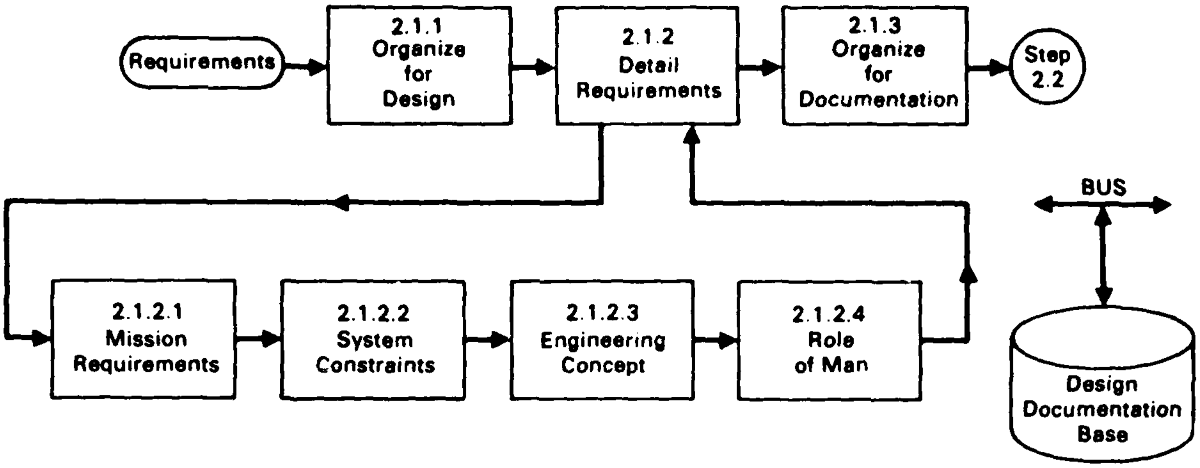
2.1.2.1 <u>Define Mission Requirements</u>. Consult with the sponsors or end-users to ensure a complete list of mission requirements, as follows:

- o <u>Identify the Mission Profile</u> and its probable variants. For each variation, find the permitted ranges of reliability and performance.

- o <u>Query End-Users</u> and operational commanders repeatedly, to ensure that requirements are fully thought out.

- o <u>Be Ready to Expand or Change</u> the requirements, based on design experience. The idea that requirements should be "frozen" at any point is a poor one.

Exhibit 2.1C
Detail Requirements



2.1.2.2 <u>Define Constraints</u>.

- <u>Look for Unstated Constraints</u> which are understood by users, but are not expressed in writing. Find what cost limits apply. Find in what environments the system must perform, and what non-normal conditions may arise.

- <u>Look for Informal Constraints</u>. In particular, watch for social, organizational or political considerations which may limit the permitted choices of design.

2.1.2.3 <u>Specify the Engineering Concept</u>. Any new system is initiated in response to a technical opportunity. The engineering concept states how that opportunity is to be exploited. It ensures an understanding of what the technical opportunity is believed to be, and ensures that it has been realistically evaluated.

The engineering concept should be stated in terms of the existing (analogous) technology, plus a required new development or "delta". The delta may range from a minor exploitation of off-the-shelf components, to a major technological breakthrough. The new system will be developed by applying the development delta to the existing technology, to meet the engineering requirement.

- <u>State the Technical Opportunity</u>.

- <u>State the Existing Technology</u> from which the system will be derived.

- <u>State the Engineering Requirement</u> in terms of quantified technical performance and acceptable ranges of performance.

o State the Development Delta in terms of off-the-shelf technology to be used, new science or technology required, and acceptable ranges of technological risk.

o State the Expected Costs for hardware, operation, support, and development.

o State Non-Dollar Resources which are assumed, such as existing hardware, facilities and organizations.

o Describe Related and Interdependent Technologies, existing or under development.

o Ensure That a Plan Exists for continued consultation, to modify the engineering concept, based on lessons learned during development.

2.1.2.4 Specify the Role of Man. The "role of man" is a statement of how humans will be employed in a new system. It is parallel to the engineering concept, which states the expected role of technology. The role of man statement reacts to the engineering concept, since it states how the new technology will affect human participation. Just as the engineering concept was defined in terms of an old technology plus a delta, the role of man can be defined in terms of the human role in a known system, plus the organizational delta, or change in the human role which a new system will require.

o State the Role of Man in terms of how humans are used in an existing analogous system, and how the new system will change that role.

o State the Expected Levels of Automatic Control, and how human control will continue to be exercised. Refer to subsection 5.1, LEVELS OF AUTOMATION, to find appropriate control models.

o State the Expected Human Demands for skill, knowledge, experience, complexity of decision, and speed of response. State acceptable ranges of human performance, and human error rates.

o State the Level of Manning which is assumed. State how skilled people will be acquired, whether by selection, training or job experience. State critical training lead times.

o State the Acceptable Balance between human skill and automation. Describe relative human and automation costs in dollars and procurement lead times.

o Specifically State any requirement for manned vehicle control, and the rationale for that requirement.

o State How Human Control will be maintained over automation. Include requirements for command and policy-level control, how responsibility will be apportioned for catastrophic human or engineering failure, and requirements for key information to be displayed or recorded.

o Describe the Expected Structure of the human organization.

- Plan for Continued Consultation, to modify the role of man, based on lessons learned during development.

2.1.3 Plan for Documentation

The engineering system is usually well documented in its final form. The human subsystem is often less carefully documented, and the allocation of functions (AOF) is often not documented at all, either because AOF decisions are not made systematically, or because the engineering documentation is believed to be enough. Such documentation will not support effective AOF. Documentation is the means by which engineers crystallize their ideas, and communicate them across time and specialty boundaries. AOF decisions, in particular, depend on communication between the engineering and human factors disciplines, and upon the availability of good formal documentation for both the emerging engineering and human subsystems. That documentation must use a common terminology and conventions, and must always be accessible to all members of the design organization.

- Establish a Design Documentation Base (DDB) before any design or analysis begins.

- Maintain Historic as well as current design data. Record the rationale for decisions. Keep records of directions taken in error, so they need not be repeated.

- Maintain Separate Records of the engineering design, the human factors design, and AOF decisions. Be sure those records are coordinated at points of interface.

- Establish Requirements for each specialty team to make and update records. Do not permit secrecy or delay.

- Provide Access Systems to the design data base.

- Identify Persons Responsible for the design data base at each organizational level.

2.2 IDENTIFYING FUNCTIONS

This is step 2.2 of the design decision cycle, as illustrated by Exhibit 2.2. At this step the designers decompose the system under design into functions which can collectively perform the mission. This decomposition is progressive towards finer detail, as development proceeds through successive cycles of hypothesis and test.

2.2.1 First-Level Decomposition

The first step is to define the system in terms of gross or major functions. For instance it might be defined into an airborne and a ground function. The actual initial decomposition is more likely to be into 10 to 20 major functions, and it can be accomplished in several ways:

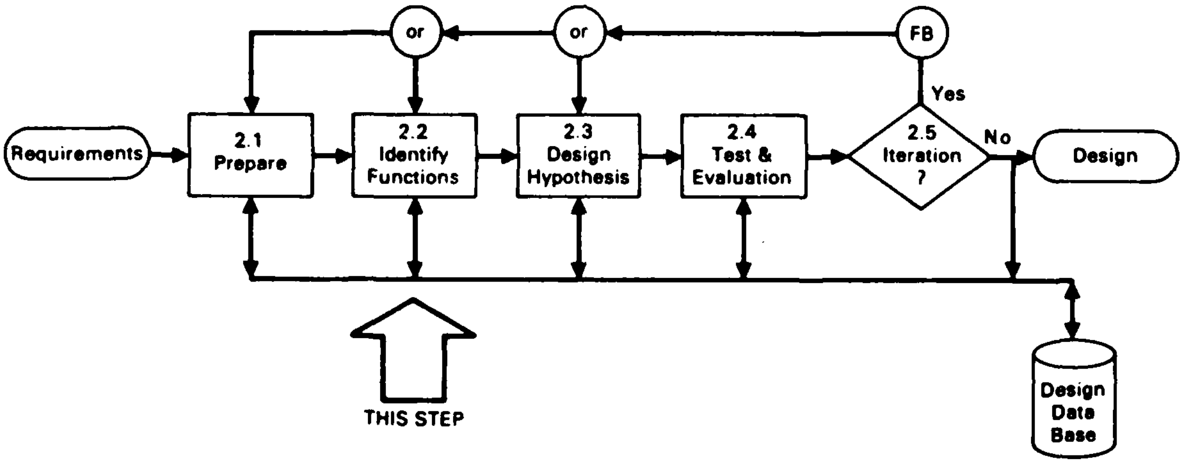
o By Invention. Given an operational goal, the designers may invent an original set of subsystems or substates by which the goal can be achieved.

o By Partition. Given a prior system concept or an analogous system, the system can be broken down by analysis into a useful set of subsystems and mission states.

o By Addition or Subtraction. Given the functions of an analogous prior system, functions may be added or subtracted as required to achieve the development delta (defined in Subsection 2.1).

Exhibit 2.2

The Design Decision Cycle – Step 2.2



2.2.2 Recognizing a Function

This decomposition often produces a set of functions which seem to be equivalent to subsystems, but a function is not a subsystem. As defined in Section 1, a function is a condition or event that is needed to achieve the mission, defined so far as possible in the abstract, and in terms of inputs, outputs and constraints.

o Functions Are Not Subsystems. For instance the function "maneuver aircraft on the ground" may exercise the subsystems of engine control, nose wheel steering, and rudder control.

o Functions Are Not Tasks. For instance the function "maintain a fixed heading" includes the pilot task "enter azimuth setting into controls" and the automation task "control rudder movement."

o Functions Relate to System States and Transitions. During its lifetime a system must assume a series of dynamic and transitional states. These include test, training, maintenance, abnormal and degraded states, as well as the normal operating ones.

- State Transitions define the paths by which transitions occur between states.

- Required Functions are those functions necessary to achieve the minimum set of states and transitions required for mission completion.

- Accessory Functions are those desirable to provide for abnormal, emergency, test, training, or additional capabilities.

- Control and Display Functions are those required to (1) recognize stable or unstable states, (2) maintain stable states, (3) effect transitions, and (4) diagnose failures.

2.2.3 Operational Definition of Functions

The first-level identification of functions we have described is purely provisional - it is a place to start. These functions will normally undergo many changes in response to the needs of design, and the final identification of functions will be the result of that interaction. To see how this happens, we will look forward briefly into subsections 2.3, 2.4 and 2.5, and observe how functions are operationally defined during the design cycle.

- Design Hypothesis. Each function that was provisionally identified in the current step (2.2) becomes a design requirement. Next, in the Design Hypothesis step (2.3), the designers will invent a hypothetical means for performing that requirement. This will include an engineering solution, a human factors solution, and a hypothetical allocation of functions (AOF). If at this point suitable solutions cannot be found, it may be necessary to redefine the function. The designers may go back to step 2.2 and change the identities of functions, or decompose them into smaller, more manageable parts.

- Test and Evaluation (T&E). Next (step 2.4) the design hypotheses proposed at 2.3 are subjected to test. If T&E detects weakness in a hypothesis, further redefinition or repartition of functions may be necessary.

- Iteration. In the last step (2.5) T&E data are used to initiate cycles of feedback, correction and repartition. During the feedback process, functions may need to be further redefined.

- Repartition. When any function meets test criteria at the gross level of definition, it is returned by the iteration step (2.5) to the definition step (2.2), to be decomposed into smaller functions, until functions have been defined to the required level of detail.

- Operational Definition. Thus the final definition of functions results from interaction with other decisions of design during the operational design process, and is determined only in part by the provisional definition made at step 2.2. That provisional definition provides the input to step 2.3, the Design Hypothesis.

2.2.4 Documentation

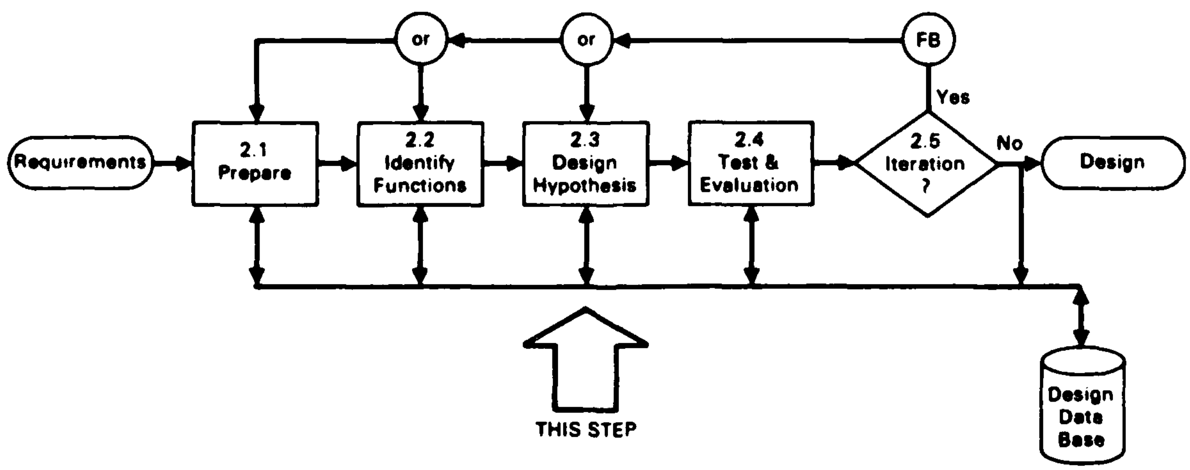
It is important to maintain an auditable record of the allocation of functions, including how those functions are provisionally defined and later modified. This record is part of the Design Data Base, and will be useful to guide the redirection of effort when design hypotheses fail. When design is complete this record will show the final set of gross functions which emerged from the operational definition process, plus many levels of subdivision for each function. Later this record will be useful for trouble-shooting, retrofit and redesign.

2.3 DESIGN HYPOTHESIS

This is step 2.3 of the design decision cycle, as shown by Exhibit 2.3A. Here the designers formulate a provisional design solution (or design hypothesis) for each of the functions defined at step 2.2. The three elements of the design hypothesis are (1) an engineering hypothesis, (2) an allocation of functions (AOF) hypothesis, and (3) a human factors (HF) hypothesis (see Exhibit 2.3B). Each element of the design hypothesis is proposed as a provisional solution only, to be confirmed or corrected later, especially during Test and Evaluation (T&E), the next step of the design cycle.

Of the five steps in the design decision cycle, this one is most critical to AOF. Given this importance we will come back to it later in Section 3, which will describe the design hypothesis as a detailed procedure. Here in step 2.3 we treat it only briefly, as a step in design.

Exhibit 2.3A
The Design Decision Cycle – Step 2.3



2.3.1 The Engineering Hypothesis

The engineering hypothesis is a proposed hardware design for one function. The designers respond to the system requirements, treating one function at a time, by making a best initial judgment of the engineering means by which the function should be performed. Each hypothesis covers both hardware and software. During the early phases of systems analysis and preliminary design, these hypotheses are in general terms only - in terms of equipment categories and generalized subsystem descriptions. Later, as the design develops and the functions are stated in increasing detail, the engineering solutions will become particular, describe smaller elements, and be more equipment specific. Finally the point will be reached at which functions are partitioned at the lowest level, and the engineering hypothesis will specify particular components, software, and configurations of controls and displays.

This hypothesis is developed by an engineering team, ideally with the participation of human factors engineers. The products are a generalized hardware assumption, a generalized software assumption, an analysis of system states and transitions, and a list of control requirements.

2.3.2 The Allocation of Functions Hypothesis

The allocation of functions (AOF) hypothesis is a proposed boundary, for one function, between the engineering and human factors subsystems. The designers react to the engineering hypothesis just formulated. Given that engineering solution, they ask what relative roles will be required for humans and machines. A hypothesis is then proposed for the optimal sharing of system responsibilities between engineering (equipment, facilities, software, controls, automation) and humans (users, commanders, operators, maintainers). This is the boundary between humans and machines, the "man-machine interface."

During this step the designers may be forced to reject prior decisions. They may reject a requirement, repartition a function, or modify the engineering requirement. As indicated by Exhibit 2.3B, they produce two lists of control tasks, one to be performed by humans and one by automation. This last list of automation tasks will become an additional requirement for engineering design.

The AOF hypothesis should be developed by an interdisciplinary team which includes both engineering and human factors members.

2.3.3 The Human Factors Hypothesis

The human factors hypothesis is a proposed human organizational design for one function. The designers react to the allocation of functions (AOF) hypothesis, and especially to the list of human control tasks. Given those requirements they ask what human organization can optimally perform them. The HF hypothesis implies a general plan including such elements as an organizational structure, a set of required skills, a training plan, and a set of job aids or procedures. As the result of this effort, the designers may be forced to reject or reconsider prior decisions of the design decision cycle.

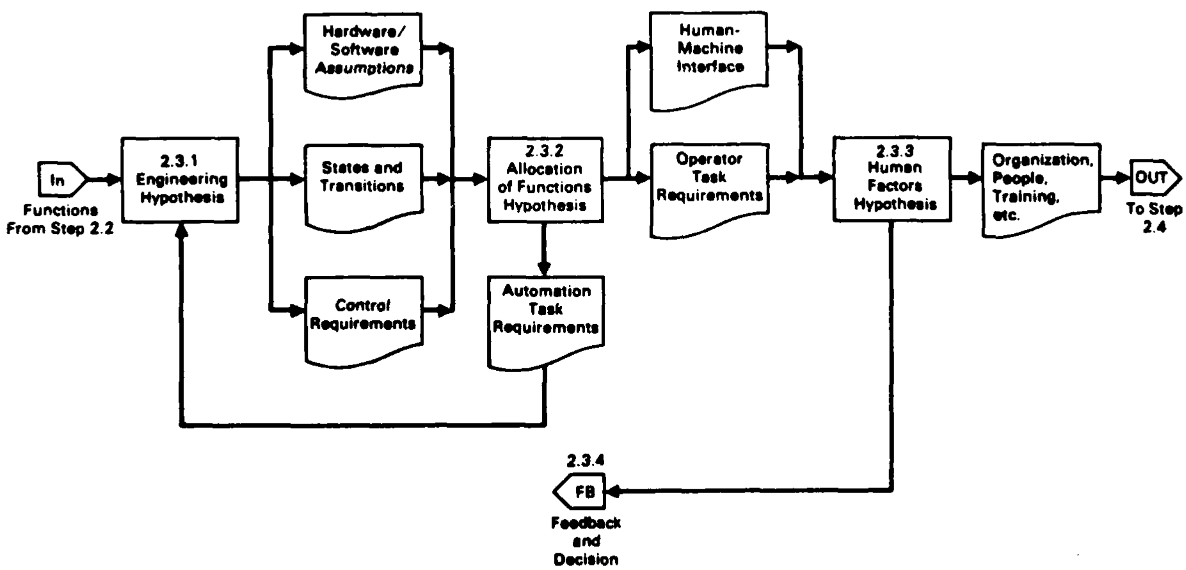
The human factors hypothesis should be developed by a HF design team which includes engineering members, and which benefits from consultation with experienced users of similar systems.

2.3.4 Iteration and Feedback

As we have said, design is characterized by cycles of hypothesis, test, feedback, correction, and the progressive development of detail. These feedback loops are most obvious at the formal project level, but they are present at all levels of design, including within the design hypothesis. Note that each of the three steps just described can conclude with feedback and reconsideration of prior steps of design.

The iteration represented by Exhibit 2.3B includes a cyclic repetition of the three included hypotheses (engineering, AOF, HF) until they are mutually compatible, and until each of the functions defined at step 2.2 has been fitted with a suitable design hypothesis. When this has been done, the effect is to define for the whole system a hypothetical engineering subsystem, allocation of functions, and human factors subsystem. Later these steps will be repeated to develop the design at increasing levels of detail.

Exhibit 2.3B
Design Hypothesis



2.4 TEST AND EVALUATION (T&E)

This is step 2.4 of the design decision cycle, as shown by Exhibit 2.4A. Here the designers evaluate the emerging design, using first deductive and then empirical tests. Tests are applied first to single functions, and later to the integration of functions in the system as a whole.

Exhibit 2.4A
The Design Decision Cycle – Step 2.4

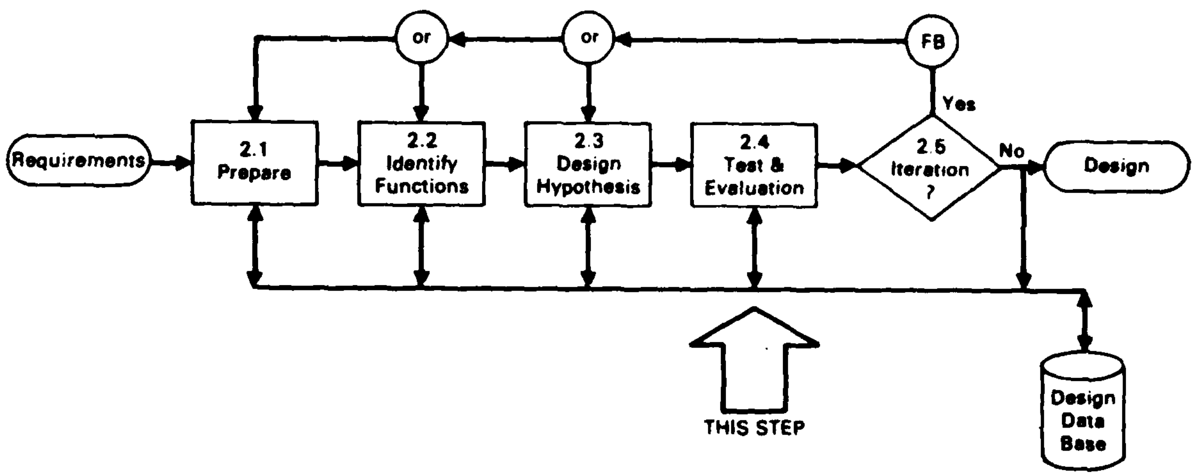
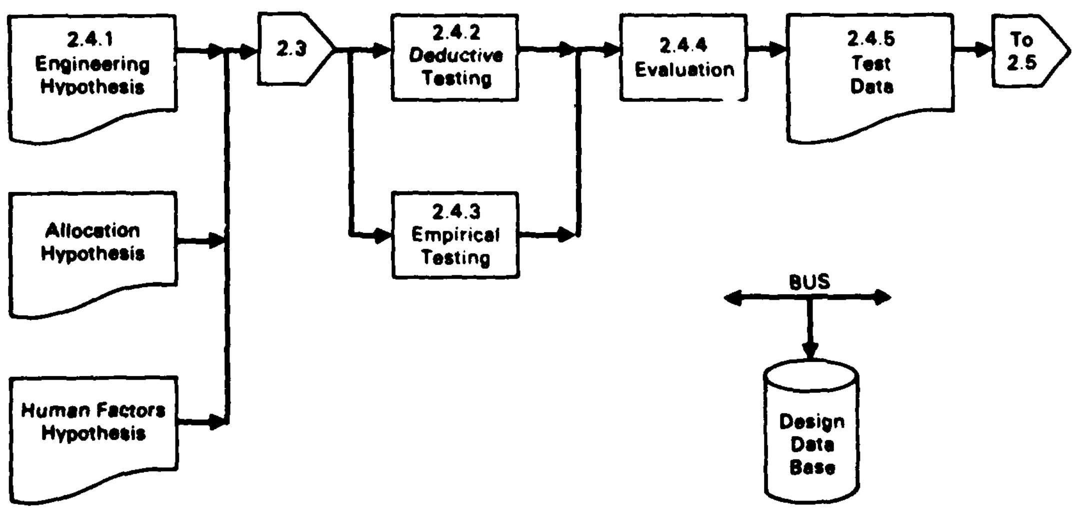


Exhibit 2.4B
Test And Evaluation



2.4.1 Entry Conditions

Test and evaluation (T&E) operates on the hypothetical elements of design described in Subsection 2.3. At first those elements exist only in functional design documents which describe major functions and generalized design solutions. Later they are described in greater detail, and then become highly specific. At that point they may be expressed in models, mockups or prototype equipment, and at that point the design might be described as "provisional" rather than "hypothetical." (Refer to Exhibit 2.4B).

2.4.2 Deductive Testing

So long as the design exists only in documentation, it cannot be tested empirically, but only by deduction and against a priori criteria. Deductive testing is relatively rapid and inexpensive, and will remain a major tool even after prototype hardware has been built. Deductive tests are applied (1) to each function individually to test the design hypotheses, and (2) to the system as a whole to test function-to-function interactions.

2.4.3 Testing Single Functions

Each defined function must be examined, asking at least the following questions.

2.4.3.1 Does the Engineering Solution Meet Criteria? Is the engineering solution suitable? Is it feasible at an acceptable level of technological risk? Is it the best technology at its cost level? Will calculated performance meet mission requirements within stated constraints? Answers are derived by engineering analysis.

2.4.3.2 Does the Human Factors Solution Meet Criteria? Is the human factors (HF) solution suitable? Is it achievable within time and human resource constraints? Is it the best human organization for the cost? Can it exercise effective system control? Is it consistent with the role-of-man statement? Answers are provided by the judgment of human factors engineers.

2.4.3.3 Are Engineering and Human Costs in Balance? Is the predicted cost of engineering balanced against human costs? They need not be equal, but should minimize total system cost for the life cycle of the system. Consider supporting hardware and human costs as well as direct costs.

2.4.3.4 Is the Allocation of Functions Suitable? Does the allocation of functions optimize the role of humans and machines in performance of the mission? See paragraph 2.4.5, "Allocation of Functions Test Criteria."

2.4.4 Testing the System as a Whole

Next the interaction of functions must be tested for the system as a whole. Ask at least the following questions.

2.4.4.1 Is the Engineering Subsystem Suitable? Do the engineering hypotheses for all functions taken together add up to a coordinated engineering subsystem? Are they technically compatible? Do functional inputs and outputs match? Is there a consistent level of technology across the system? Are costs consistent? Are development times acceptable? Will the engineering subsystem support all mission states? Answers are derived by engineering analysis.

2.4.4.2 Is the Human Subsystem Suitable? Do the human factors hypotheses for all functions add up to a coordinated human factors subsystem? Are they organizationally compatible? Are requirements for skill, ability, training and experience reasonably consistent? Are manning and training objectives achievable within time and resource constraints? Could costs be reduced by a different HF design? Will the human organization support all mission states? Is it consistent with the role of man statement?

2.4.4.3 Are Engineering and Human Costs in Balance? Is the expected cost of humans in balance with that of engineering? Could cost or performance be improved by a different balance?

2.4.4.4 Is the Allocation of Functions Optimal? Does the allocation of functions optimize the capabilities of people versus machines at the whole system level? The formal tests of paragraphs 2.4.5 and 2.4.6 will examine that issue further.

2.4.5 Allocation of Functions Test Criteria

Four tests are suggested to evaluate allocation of functions (AOF). In each of these tests, data from the HEDB should be consulted.

2.4.5.1 Can the Human Subsystem Meet Engineering Performance Requirements? The first test is whether each designated (or implied) job can be performed to criterion by a human. When viewed purely as an engineering component, can a human meet the time, speed, perception, processing and memory demands of each function? Can a human meet the demands imposed by all functions to be encountered in a job? Use the human-machine models of Section 5 to make these judgments.

2.4.5.2 Can the Human Subsystem Meet Human Performance Requirements? This test expands the question of human suitability, to ask whether humans can perform as required considering their environmental needs, learning limits, physical characteristics, reliability, response to stress and fatigue, psychological vulnerabilities and social needs. These questions require the judgment of a human factors engineer.

2.4.5.3 Is Cognitive Support Adequate? This test asks whether the human decision maker will be given sufficient information to meet decision requirements. Guidance for this question is provided by Subsection 4.4, Affective and Cognitive Support.

2.4.5.4 Is Job Satisfaction Optimal? This test examines factors which lead to human acceptance of a job. Subsection 4.4 provides guidance on this question also.

2.4.6 Empirical Testing

The definitive test of a system is actual performance. Therefore we seek such empirical tests as soon and as often as possible. When elements of a system can be modelled, represented in mockups, or built as prototypes, we test them in simulated or real performance. Ideally, this is done in real field settings by typical human users.

As the system develops there should be an evolution toward greater dependence on empirical tests, but because such tests are more expensive and time consuming, they can never replace deductive tests, which continue for the life of the system. Empirical tests can be used to validate and calibrate deductive tests, and are the definitive measure of end performance.

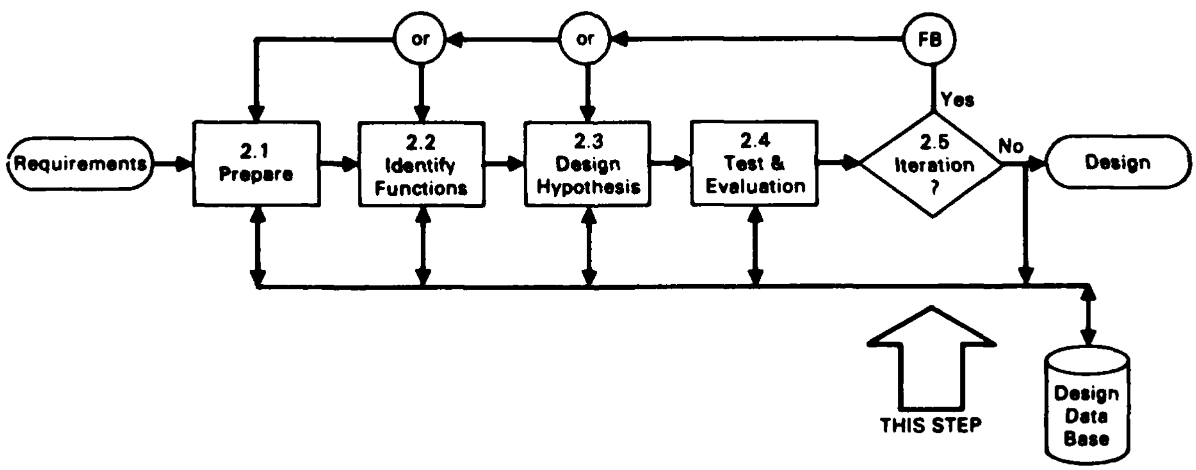
2.4.7 Evaluation

Tests, whether deductive or empirical, produce data and not decisions. Test data must be evaluated, and translated into analyses of what is right or wrong with the evolving design. Then decisions can be made as to what should be done to further improve the system.

2.5 ITERATION

This is step 2.5 of the design decision cycle as shown by Exhibit 2.5A. This step produces a decision, based on test data, as to whether the design hypotheses meet criteria, and if not, what feedback treatment is required. In this step each function is reviewed for the adequacy of its design hypothesis, and all functions are compared for function-to-function integration. When criteria are met, the design hypotheses are accepted, and

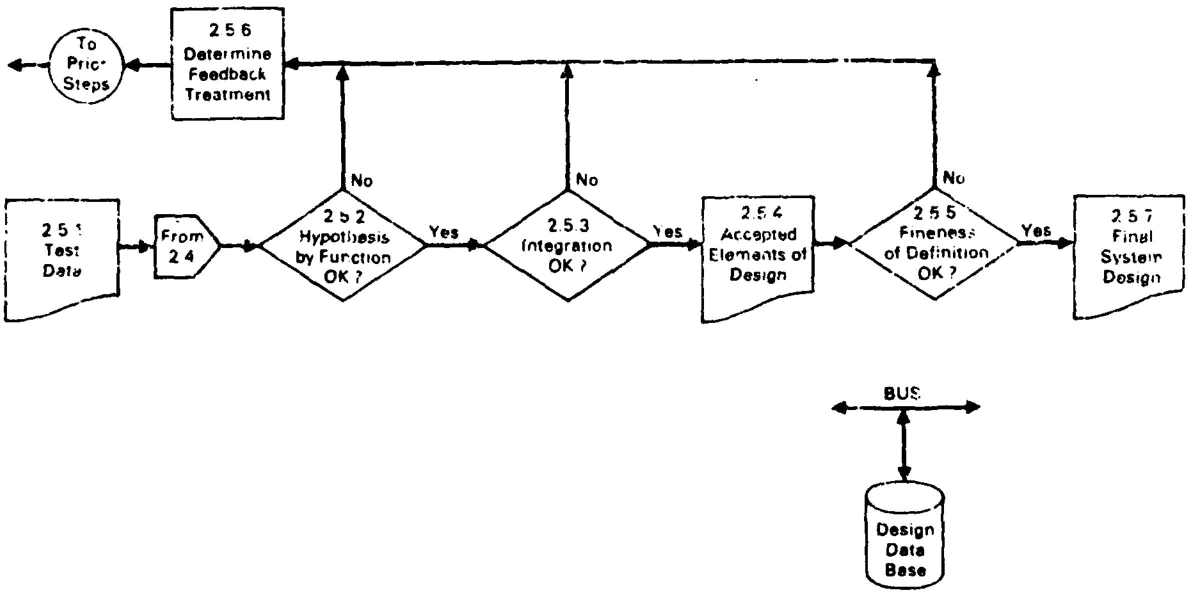
Exhibit 2.5A
The Design Decision Cycle – Step 2.5



they become part of the design at its current level of definition. Functions are then reviewed for their fineness of definition and are fed back for repartition until the required level of detail is achieved. These cycles of iteration, redesign and repartition continue until all functions meet criteria at the required level of detail, and the design is complete.

Block 2.5.1 of Exhibit 2.5B represents the test data at any stage in design. These data consist of quantified actual or predicted performance, descriptive data, and expert opinion. They may be contradictory, and often are not related to any criterion. At this point the design team must decide which functions should be accepted, and which should be returned to prior steps for redesign. This is the point at which it is conventional for the buyers of the system, and preferably the sponsors and end-users, to take part in evaluation. Hereafter we will refer to decisions as being made by the designers, with the understanding that the buyers should participate as well.

Exhibit 2.5B
Iteration Of The Design Decision Cycle



2.5.1 Entry Conditions

Step 2.5 operates on test data from step 2.4. These data have been incompletely evaluated in that the decision to accept or reject each element of design has not been made. These data include:

o <u>Data on Individual Functions</u>. They include data by function on the probable suitability of (1) the engineering hypothesis, (2) the allocation of functions hypothesis, and (3) the human factors hypothesis.

o Data on the Interaction of Functions. They include data by subsystem or for the system as a whole on the apparent effectiveness, costs and future performance of (1) the engineering subsystem, (2) the human factors subsystem, and (3) the system-wide allocation of functions.

2.5.2 Acceptance by Function

Tests produce data, not decisions. These data must be translated into further actions within the design decision logic. First the design team looks at the data function by function, to decide which functions require further consideration. Two major considerations control this decision: system requirements, and cost tradeoff analyses.

2.5.2.1 System Requirements. Obviously, each function must meet the system requirements defined at step 2.1. Predicted performance must meet mission performance requirements, be within constraints, match the engineering concept and fit the role of man definition. Always bear in mind that if necessary, requirements can be renegotiated.

2.5.2.2 Cost Tradeoffs. The next question is whether cost or effectiveness can be improved by further design effort. Cost tradeoff data developed during the RDT&E step will apply, and the following tradeoffs are of particular interest:

o People versus Machines. Consider the expected balance between equipment and people, for the life cycle of the system. Allocation of functions should maximize effectiveness by allocating functions to whichever means will perform best, and minimize costs by the same decisions.

o Costs of Design. A final consideration is the costs of the design effort itself. In general, a design hypothesis should continue to be reconsidered so long as the costs of further design effort are justified. Many cycles of effort should lead to better design, and to a reduced number of design errors. It is cheaper to correct design errors on paper than by retrofitting hardware. On the other hand, design itself costs money and cannot continue indefinitely. This usually is an academic issue, since the schedule never provides all the time the designers need.

2.5.3 Integration of Functions

Once hypotheses are acceptable function by function, they must be examined as a whole. At this point the collective cost and effectiveness of the engineering and human subsystems are taken into account. Again the major considerations are system requirements and cost tradeoffs. The predicted collective performance of each subsystem is compared to requirements, and cost tradeoff data are examined. Elements of the design which can benefit from further reconsideration are returned to that step in design which seems to have been deficient. Here the problem is to realistically assess the interaction of functions across the system.

This assessment can be simplified by comparing three or four functions at a time. The designers compare (and may use mathematical models) those functions which are critically active during each single system state or transition, and when an unacceptable integration of functions is detected, return those functions which are at fault for redesign.

2.5.4 Accepted Elements of Design

Any function which meets criteria at blocks 2.5.2 and 2.5.3 becomes an accepted element of design (block 2.5.4). These elements do not constitute a complete design, since some functions were returned for redesign and are missing, and most functions are not yet decomposed to the required level of detail.

2.5.5 Fineness of Definition

Before functions are repartitioned, they are ordinarily allowed to accumulate as accepted elements of design (block 2.5.4) until those elements represent a reasonably complete design at a given level of detail. Such functional levels may correspond to standard phases of design, such as "system definition," "preliminary design," or "prototype development." More frequently, several levels of partitioning occur between formal phase points. In any case functions are periodically returned to step 2.2 for further decomposition (block 2.5.5). The fineness of definition required varies, but must be sufficient to permit the identification of specific system components and specific human tasks.

2.5.6 Determine Feedback Treatment

When a function must be reconsidered it may be routed to any prior step of design, depending on the defects of the function. Most frequently the identified defect is in the engineering or human factors hypothesis, and the function is returned to the appropriate substep of step 2.3, the design hypothesis. In other cases a function may be too broad to permit a good single solution, or a better solution may be achievable if the boundary between two functions is redrawn. Such functions, and those returned for repartition, are returned to step 2.2 for redefinition. Finally, cases occur in which the design criteria are too restrictive, and such functions may require a renegotiation of requirements at step 2.1.

2.5.7 Completion of Design

When a function has been partitioned to the level required and meets criteria it becomes an element of the final design. When all functions have passed that test the design is complete.

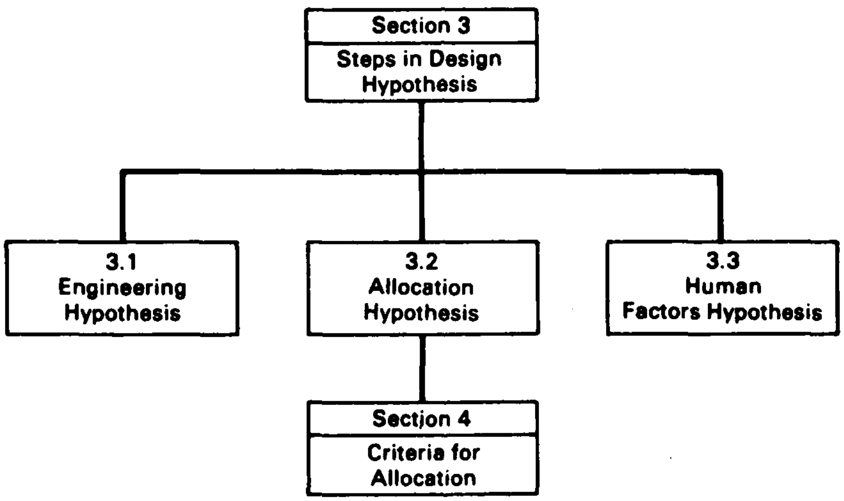
Some texts consider "functional design" to be complete when a set of functions is defined but before any physical components have been selected. It is useful to have such a "functional design" phase, and to defer concrete hardware decisions as long as possible to keep the options open. But in practice the iterative process of defining functions, developing hypotheses and testing must continue throughout the design process. Even then it does not stop. It continues throughout the operating life of the system, and contributes to the processes of evaluation, modification, redesign and disposal. The design decision cycle continues so long as any element of the system may be subject to change or evolution.

SECTION 3

STEPS IN THE DESIGN HYPOTHESIS

This section expands upon Subsection 2.3, The Design Hypothesis. That hypothesis is the heart of design logic and contains many actions critical to the allocation of functions (AOF). Therefore we will describe it in procedural detail. To summarize Subsection 2.3, the design hypothesis consists of three included hypotheses, (1) an engineering hypothesis, (2) an AOF hypothesis, and (3) a human factors hypothesis (Exhibit 3). They are normally made in that order. They may occur as part of the designer's unconscious thinking processes, or formally in a design procedure, but the elements of the AOF decision are embedded in those hypotheses, as we will see. Before proceeding, it will be useful to examine some characteristics of the design hypothesis.

Exhibit 3
Steps In The Design Hypothesis
(Derived from Exhibit I)



<u>How to Approach the Design Hypothesis</u>

The design hypothesis is the inductive step in systems development, and it is not achieved by deductive logic. There is no rule or formula. We tend to regard engineering and system development as exact sciences. We may therefore expect design to be achieved [illegible] mathematical or systematic procedures. But hypothesis is the inventive step of design, a step which depends on creative logic, exploration and judgment, rather than on method or algorithm. In fact, the development of a design hypothesis is characterized by the following conditions:

o Not all variables are identified.

- Many identified variables cannot be measured.
- Most decisions are value laden.
- Most decisions include a statistical estimate of risk.
- All options are open, including some options which must be discovered.
- The human element is particularly hard to foresee.
- Even engineering predictions depend on expert opinion.

Professional Judgment . Under these conditions we depend ultimately on the judgment of informed professionals. At each step in the process we can find some limited quantitative information. This may include data on expected engineering performance and on the control demands which a hypothesis will impose, but these data are speculative, since the new system does not yet exist. We can predict human performance only by analogy to past experience. What firm data we have must be evaluated against the variables and unknowns, using expert judgment. There are proven ways to proceed, which include the following:

Use a Panel. Professional judgment will be most effective if it is a consensus and represents several disciplines. Such judgments can be made by a panel procedure, which should have the following features: (1) Documents and resources should be assembled beforehand. (2) Professional qualifications should include a senior member with broad systems experience, human factors or equivalent members, and design engineers from each specialty concerned. (3) Meetings should be formal and controlled by an agenda. (4) Records should be kept of alternatives considered, decisions made, and the rationale for decision. (5) A forced decision strategy should be employed to speed design.

Analogy to Known Systems. A useful source of information will be experience from older analogous systems. In fact, this is the source of all design data, predictive or speculative. Analogous systems are particularly useful when there are records or anecdotal data about human performance in those systems; unfortunately such data are seldom preserved. This leaves only the personal experience which members of the team may have had with such systems.

User Experience. Possibly the single most useful source of information is the experience of users. Experienced operators, commanders, pilots and mid-level decision makers should be present on the design team, or available for consultation.

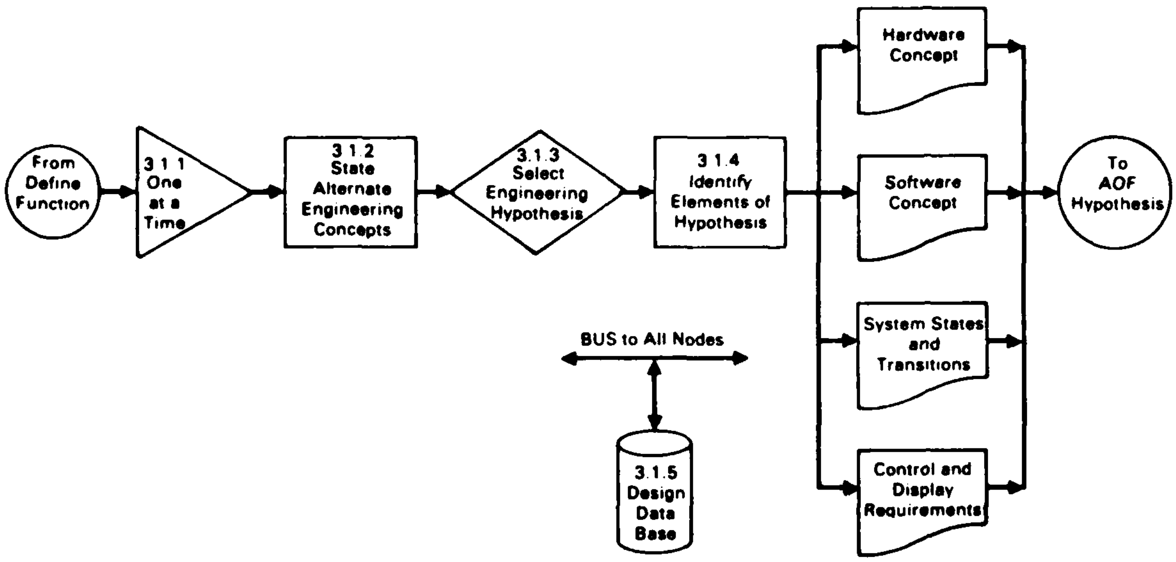
Forced Decisions. A panel will be cumbersome if required to actually agree on each point. Several hundred separate decisions must be made during each of many design cycles. It is more useful to make those decisions quickly and test them repeatedly than to seek perfection the first time. An authoritarian procedure is suggested, in which discussion is followed by a brief effort to reach consensus, but concluded if necessary by a leader's prescribed decision.

The considerations just listed should be kept in mind, while formulating design hypotheses using the three step procedure which follows.

3.1 THE ENGINEERING HYPOTHESIS

An engineering hypothesis is the first step in design hypothesis, and logically precedes other hypotheses. Subsequent steps react to that hypothesis, since it predetermines that certain roles will be performed by machines. By this hypothesis the designers propose an engineering solution - a potentially optimum engineering means of meeting mission requirements for one function. This hypothesis is stated in functional terms.

Exhibit 3.1A
The Engineering Hypothesis



3.1.1 <u>Treat One Function at a Time</u>

Functions identified earlier at step 2.2 constitute a provisional list of functions. At first this list contains a few major functions; later it will contain many functions narrowly defined (see Exhibit 3.1A, block 3.1.1). Select functions from this list one at a time. Normally, choose them in the order of their importance, mission-critical functions first, then non-critical and support functions. If there are functions which are time- or technology-critical to design - those which may be technically difficult to achieve or which lie on the project critical path - consider them critical even if they are support functions.

Use an engineering team to form this hypothesis. This does not mean that it can be based on narrow engineering criteria. Since this hypothesis constrains the subsequent AOF and human factors hypotheses, it must be made intelligently and with multidisciplinary consultation. In particular, consider the following:

- Human Factors. Consider the needs of users and maintainers, and the costs of humans in the system. Use human factors consultants. Consult operators and maintenance personnel.

- Other Functions. Although only one function can be considered at a time, remember that all will eventually be integrated into one system. Consider, to the extent feasible, the probable requirements of other functions, especially those which have already been defined.

3.1.2 State Alternate Engineering Concepts

Identify the alternative engineering means by which a defined function might be accomplished (see Exhibit 3.1A, block 3.1.2). Typically these are known technologies which can be applied "off the shelf" or with modifications. Less frequently they are new inventions, based on analogous technology but with new qualitative capabilities. Occasionally they may provide a totally new technology by exploiting theory or research.

This step is the heart of the engineering hypothesis and the point at which creative development or invention takes place; a permissive criterion must apply. Concepts should be considered even though they may be vulnerable to criticism or appear unlikely choices. Consider as one alternative performance of a function by humans alone - one engineering option is not to use machinery.

State engineering alternatives, when possible, in functional terms. Keep the design options open even if an off-the-shelf technology seems the obvious choice.

3.1.3 Select an Engineering Hypothesis

Now select one engineering concept as a working hypothesis (Exhibit 3.1A, block 3.1.3). Choose a solution which, based on preliminary analysis, seems most likely to meet engineering criteria, and consider the probable impact of the selection upon other elements of the emerging design. To the extent that information is available, estimate the impact on the human subsystem design, interaction with other functions, life-cycle modifiability, and other system variables which may apply. Because these are numerous and mostly unquantifiable, this will be by a consensus of expert opinion. As always, describe the selected hypothesis in functional terms. Name a range of hypothesized technologies, or state the solution in input-output terms. Preserve the list of alternatives not selected, and record the decision rationale; these data may be useful if the engineering hypothesis must be reconsidered.

3.1.4 Identify the Elements of the Hypothesis

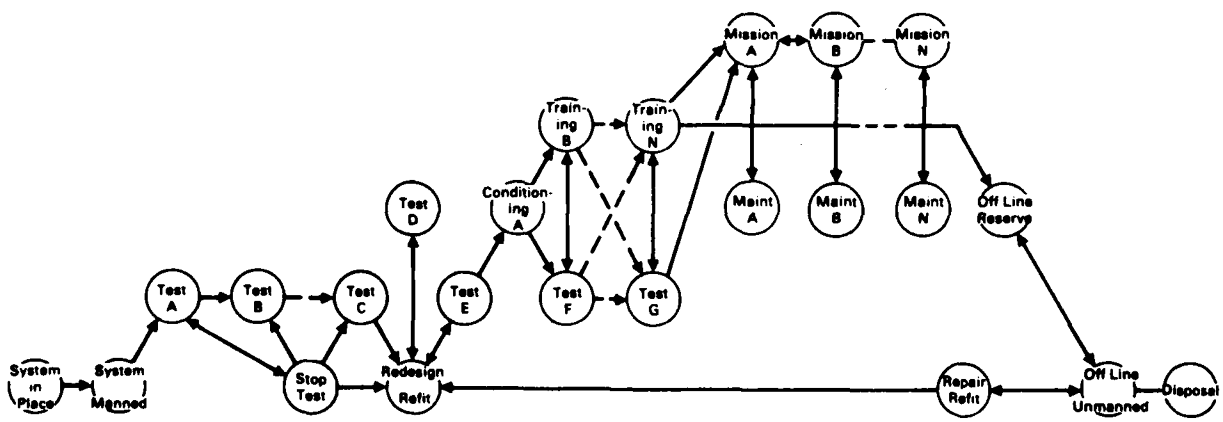
Now that an engineering hypothesis has been selected, identify the products of that decision. These will be needed to support other decisions which follow. At least four products are important, and are shown by four document symbols on Exhibit 3.1A.

3.1.4.1 The Hardware Concept. This is the implied hardware requirement, expressed in functional or performance terms.

3.1.4.2 The Software Concept. This is the implied software requirement, expressed in functional or performance terms.

3.1.4.3 System States and Transitions. Earlier, in step 2.2, the future system was first described in terms of system states and transitions between those states. Now that provisional hardware and software concepts have been proposed, it is possible to describe actual engineering states and transitions. These should now be identified and listed. They can be shown as a state and transition diagram like that of Exhibit 3.1B.

Exhibit 3.1B
Top-Level State And Transition Diagram
For Air-Ground System



The major states which the system may be required to assume during its life cycle are diagrammed and are connected by arrows representing the expected normal and emergency transitions between states.

3.1.4.4 Control/Display Requirements. System states imply control requirements to maintain their stability, and to govern transitions from state to state. Now use the state and transition diagram to identify requirements for controls. Use the control requirements to identify requirements for instrumentation and data display. As always, state these in functional terms so far as is possible.

3.1.4.5 Feedback. At any time it may be recognized that an optimal engineering hypothesis is not achievable for the function as defined, or under defined constraints. When this happens, feedback to prior steps is appropriate (not shown on Exhibit 3.1A).

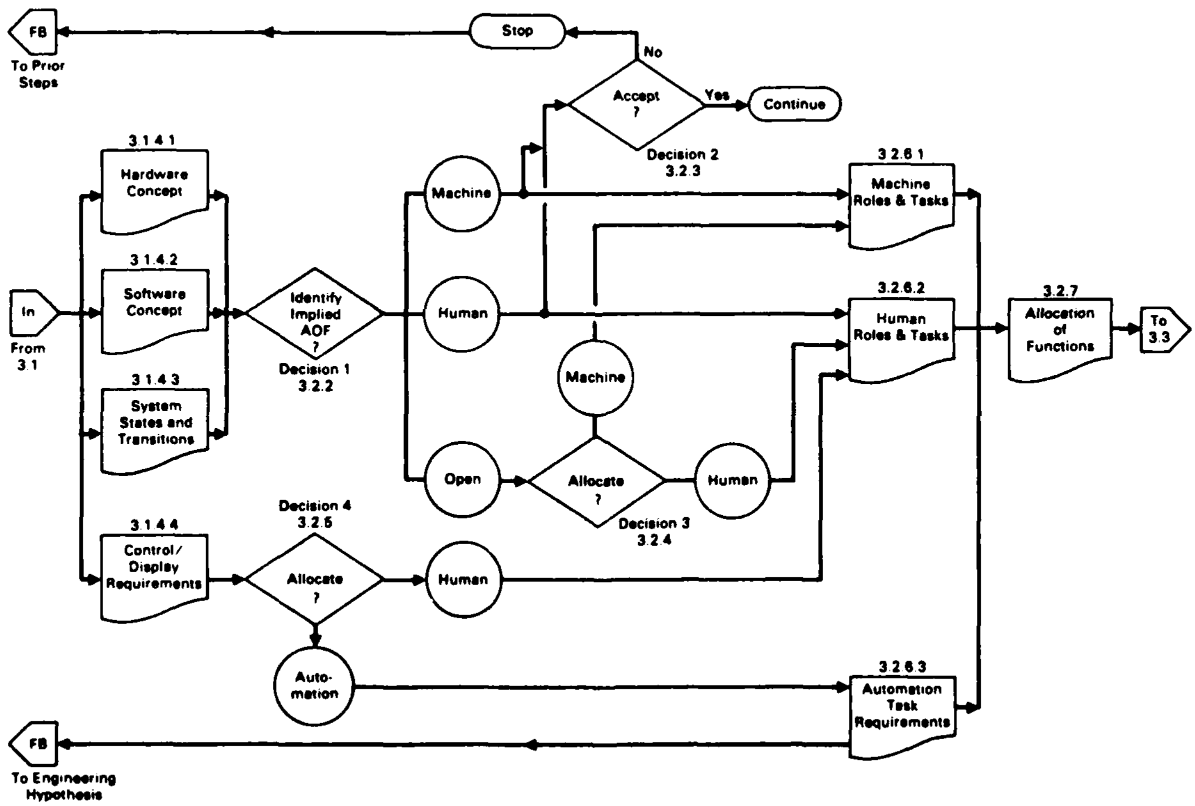
3.1.5 Documentation

Document key decisions made during formation of the engineering hypothesis. Record the alternative engineering concepts, the selected hypothesis, and rationale for selection. Record the decision products, and enter these data in the design data base (see Exhibit 3.1A, block 3.1.5).

3.2 THE ALLOCATION HYPOTHESIS

Once an engineering hypothesis is proposed it must be fitted into a system which includes people. This step makes a provisional assignment of roles and tasks to people or machines, and in so doing defines the boundary between the human and machine subsystems, sometimes called the "human-machine interface."

Exhibit 3.2A
Allocation Of Functions Hypothesis



The allocation hypothesis is made in part by a decision to accept or reject an allocation implied by the engineering hypothesis, and then by decisions to allocate those roles and tasks which are not yet determined. In particular, control tasks must be allocated to humans or automation. These decisions use decision criteria to be described later in Section 4. Early in design an entire function will rarely be allocated wholly to humans or to machines. Instead, since functions are broadly defined, they will usually be shared between the two. As design progresses and as functions become smaller and more specific, some of them will be allocated exclusively to humans or to machines. Finally, at the completion of design all functions will be defined at their finest level, and all will be allocated exclusively to humans or to machines and automation.

The allocation of functions hypothesis is formulated by an interdisciplinary team which includes both human factors and engineering members. The procedure is as follows, and as illustrated by Exhibit 3.2A.

3.2.1 Entry Conditions

Allocation of functions acts on the four products of the previous step: the hardware concept, the software concept, the table of states and transitions, and the list of control and display requirements. The first three describe the engineering solution, and the last describes tasks which must be allocated.

3.2.2 Identify the Implied Allocation of Roles and Tasks

The engineering solution implies that certain roles or tasks will be performed by machine. The term "tasks" designates actions which must be taken by people or machines, actions which can be described by a verb-object phrase such as "adjust elevator trim." The term "roles" designates more generalized actions or sets of tasks, sometimes not yet fully understood, actions which can be described by a more general phrase such as "maintain stability in flight." Thus the term "roles" applies to the description of human or machine actions early in system design when tasks are as yet undefined, and "tasks" describes the highly specific apportionment of actions which the final system design must include.

Identify those roles or tasks for whicn an allocation is predetermined by the engineering hypothesis, and those which remain open to choice. Classify them into three categories:

- o Performed by Machine. Those which, by implication of the engineering hypothesis, must be performed by machines.

- o Performed by Humans. Those which, by implication, must be performed by humans.

- o Open to Choice. Those which remain to be allocated.

This step results in a statement of how humans and machines will act together to perform and control a function. Later in design that statement may describe functions performed exclusively by humans or by machines.

3.2.3 Determine Acceptability of the Engineering Hypothesis

Block 3.2.3 of Exhibit 3.2A is the point at which the designers accept or reject the engineering hypothesis. Examine that hypothesis and decide whether it will unduly restrict future design decisions, and whether it is likely to lead to an optimal end design. This decision is made using expert judgment, and by applying the criteria of Section 4. In addition, ask the following questions:

3.2.3.1 Acceptability of the Role of Man. Are the roles (or tasks) which humans will perform acceptable?

- o Do humans retain essential control functions? Can they start or stop key processes, insert command and policy decisions, and intervene in emergencies?

- o Will humans be adequately informed? Can they understand what the system, particularly its remote and automatic processes, is doing?

- o Are tasks assigned to humans within the limits of human ability? Can humans reliably perform as required?

- o Are the conditions under which humans are used psychologically suitable? Will humans be comfortable and satisfied to perform as required?

3.2.3.2 Feasibility of a Human Factors Solution. Is a human organization to support this function feasible?

- o Will people with suitable abilities, skills, and knowledge be available? Can they be recruited, selected and employed?

- o Is the required training feasible and affordable?

- o Is a suitable job, crew and management structure achievable?

- o Is a satisfactory career structure achievable?

3.2.3.3 Cost/Value. Will the emerging allocation of roles and tasks be appropriately balanced for cost and value?

- o Would a different engineering hypothesis permit a better balance between humans and technology? (Formal cost/value analysis comes later - now make a best estimate for one function.)

If the answer to any of these questions is "no," the engineering hypothesis may constrain design too severely. Go back to prior steps of the design logic, and reformulate the engineering hypothesis.

3.2.4 Allocate Open-to-Choice Roles and Tasks

Allocate those roles and tasks which are not predetermined, using the criteria of Section 4.

3.2.5 Allocate Control/Display Requirements

One input remains to be treated. The list of control and display requirements implies a set of control and display roles (or tasks), the allocation of which is open to choice between humans and automation. Allocate those roles and tasks so as to secure optimal control performance. Use the criteria of Section 4.

3.2.6 Output Products

The AOF hypothesis is expressed by the three decision products shown as document symbols on the right of Exhibit 3.2A. They are:

3.2.6.1 Machine Roles and Tasks. This is a list of roles and tasks which are provisionally assigned to machines. Included are (1) roles/tasks which were predetermined by the engineering hypothesis and (2) those allocated by the designers.

3.2.6.2 Human Roles and Tasks. This is a list of roles/tasks provisionally assigned to humans, It includes (1) those predetermined by the engineering hypothesis, (2) those allocated by the designers, and (3) control tasks allocated to humans.

3.2.6.3 Automation Task Requirements. This is a list of requirements for automatic control functions, which becomes a requirement for additional engineering development. These data will be fed back to the engineering hypothesis step, as newly identified functions.

3.2.7 What Does an Allocation of Functions Look Like?

At this point we might ask what an allocation of functions looks like. The answer is that it differs as the design develops. Two things change: (1) As functions are partitioned to increasing levels of detail, the number of functions increases, and each function represents a smaller proportion of the whole system. (2) The allocation progresses from a set of generalized lists of human/machine roles, toward specific statements at the component level. Exhibit 3.2B illustrates an AOF document, and represents a nuclear power plant control room design after about four levels of partitioning. Such a document must include at least six kinds of information, as follows:

3.2.7.1 Identity of the Function. Field 1 of Exhibit 3.2B identifies a function. The code 1.5.2.3 in that field identifies the address of that function in design documentation, and suggests that it is number 3 among the subfunctions of the larger function 1.5.2. The descriptive name of the function follows. This function supplies filtered air to the reactor auxiliary building (RAB).

3.2.7.2 Identity of Equipment Subsystems. Field 2 identifies the principal subsystem concerned (heating, ventilating & air conditioning), and those systems with which it interacts.

Exhibit 3.2B
Contents Of An Allocation Of Functions Document

1 Function	Code 1.5.2.3. Heat, cool, vent areas of RAB with filtered air at specified temperatures. Maintain human habitability. *Cool RAB equipment. Control radiation leakage.*
2 Subsystems	HVAC RAB subsystem. RAB equipment. On/off site power. Pumped river cooling water system. Ambient air. Heating steam supply system
3 System States & Transitions	(1) Normal operation. (2) Equipment fire. (3) Equipment radiation leak. (4) Radiation leak external to RAB. (6) HVAC component failure/maintenance. (7) Transition to/from (2) (3) (4) (5) (6).

4 Control Requirements	5 Machine Roles	6 Human Roles
Maintain normal cooling level. Maintain normal heat level. Maintain required rate of air flow. • • Etc. • • Start backup fans. Filter radiation from exhaust air. Reconfigure dampers for radiation containment. • • • Etc.	Activate fans, refrigeration, heating coils, using setpoint thermostats Display temperature and flow data Display predicted data from trend forecasts. Provide abnormal parameter alarms. Provide equipment failure alarms Control dampers (normal) using program logic • • • • • • • • Etc.	*Recognize abnormality* Set thermostats seasonally by phone to plant Equipment operator Make periodic log entries per procedure Start emergency fans • • • • • Reconfigure dampers to contain radiation. *Reconfigure dampers to control fire* • • • Etc.

3.2.7.3 <u>System States and Transitions</u>. Field 3 lists the system states and transitions which must be controlled.

3.2.7.4 <u>Control Requirements</u>. Field 4 lists the control requirements which the states and transitions are considered to imply.

3.2.7.5 <u>Machine and Human Roles</u>. Fields 5 and 6 list roles (or tasks) which are assigned to humans and machines. These correspond (on this form) to identified control requirements. When a control requirement is allocated wholly to automation, an entry appears only in column 5, and when allocated to humans, only in column 6. For instance "reconfigure dampers for radiation containment" is allocated to humans and is reflected by the entry shown.

When, however, a role is still defined at a general level and stated broadly, as they are here at the 4th level of indenture, many will be performed by some combination of equipment and humans. In these cases there are entries in both columns 5 and 6, as is the case for the first three control requirements shown.

Of course, as the design approaches completion, this form will show only specific tasks, and they will be allocated specifically to humans or to automation. Control requirements will be specific actions such as "adjust no. 16 fan speed," and an action will appear in one column only, such as "adjust to standard 6600 RPM using a digital speed control".

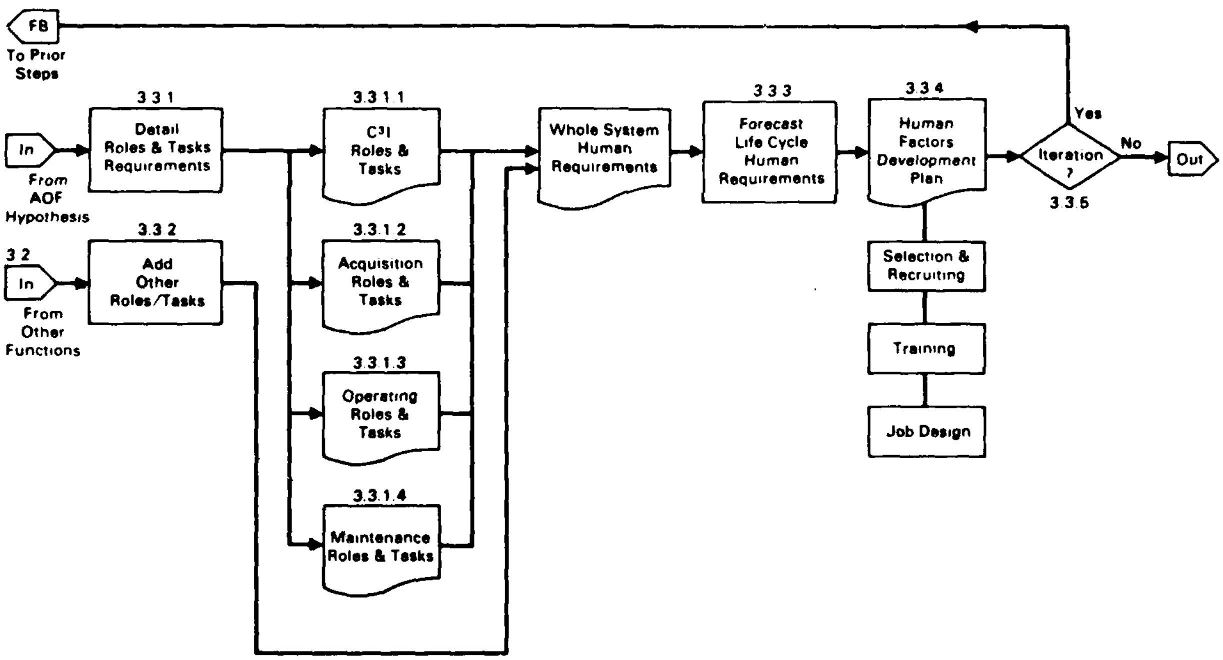
3.3 THE HUMAN FACTORS HYPOTHESIS

The third and final step in design hypothesis is to form a human factors (HF) hypothesis. This step comes last, since it reacts to requirements and constraints determined by the prior two hypotheses. By forming this hypothesis the designers specify a provisional human organization to perform the roles assigned to humans by one function. Take steps as follows:

3.3.1 <u>Detail Role/Task Requirements</u>

Principal input to the HF hypothesis is the list of human roles and tasks from step 3.2. This list is incomplete, since it is derived from operations and reflects operating requirements only. Now add requirements for communications, intelligence, maintenance, support, logistics and system acquisition. These must be estimated from the existing list of roles and tasks. Develop and list the four kinds of role/task data shown as stacked document symbols on Exhibit 3.3.

Exhibit 3.3
The Human Factors Hypothesis



3.3.1.1 <u>C^3I Roles/Tasks</u>. People are required to command, supervise, control, communicate, and provide information needed to govern and exploit the function.

3.3.1.2 <u>Acquisition Roles/Tasks</u>. People are needed to acquire the system, both hardware and human elements. They will be needed for the life of the system to conduct acquisition, test, modification, redesign and disposal. These can include personnel of the sponsor or user staff, as well as those within the system.

3.3.1.3 Operating Roles/Tasks. Operating personnel include those who pilot, control and operate the system, both its prime mission elements and support structures.

3.3.1.4 Maintenance Roles/Tasks. People are required to maintain the mission and support hardware, and to maintain the human organization. On-the-job training, for instance, is a HF maintenance activity.

3.3.2 Combine with Other Roles and Tasks

Combine these role/task data with role/task data developed earlier for other functions. These data are accumulating in the design data base. To forecast human requirements we look not just at one function at a time, but at the sum of role/task requirements, recognizing that people rarely support only one function at a time. Combine and compare human requirements of the function under design with those for all functions previously defined. Collectively these data become the whole system human requirements represented by a document symbol in the top line of Exhibit 3.3.

3.3.3 Forecast Life Cycle Human Requirements

To be useful, role/task data need to be expressed in terms of people by category and availability dates. *Estimate human performance requirements* for the system life cycle. State numbers of people required by date and category. Express time in terms of development and system schedule milestones. Express humans in terms of ability, skill, knowledge and experience.

3.3.4 Human Factors Development Plan

Hypothesize a human factors development plan. This is a plan for the acquisition and life-cycle management of the human subsystem, expressed in functional terms. At each stage of system development this plan represents the developer's hypothesis concerning the human organization for the system as a whole. Include elements such as:

- An organizational structure and management plan.
- Personnel selection criteria for ability, skill, knowledge and experience.
- Plans for recruitment, selection, and relocation.
- Training plans.
- Job design, job progression plan, crew structures.

o Operator aids, job procedures, maintenance documentation.

3.3.5 Is the Design Hypothesis Complete?

The final step in design hypothesis is to test its completion (block 3.3.5 of Exhibit 3.3). Ask the following questions:

3.3.5.1 Was a Suitable HF Hypothesis Achieved? Sometimes a good HF hypothesis cannot be found. Sometimes there is no discernible organization which can perform the required roles and tasks. If this is the case, feed the function back to a prior step of design to change the requirements, the function, the engineering hypothesis, or the AOF hypothesis.

3.3.5.2 Is the HF Hypothesis Efficient? Does the HF hypothesis impose an inefficient human organization? Does it make effective use of resources in the HF development plan? Does it impose unneeded complexity (such as special training)? If it is inefficient, feed the function back for appropriate redesign.

3.3.5.3 Does the Design Hypothesis Meet Human Factors Criteria? This is the most critical test, and it applies to the design hypothesis as a whole, rather than just the HF hypothesis. Ask the following four questions:

o Can humans provide the technical elements of performance? Use the models of Section 5, and consider the human operator as if he/she were a machine component. Partition human-machine transactions into the sequential steps of perceptual, cognitive, physiological and machine performance which they include. Determine whether humans will be able to perform each of those elements as required.

o Can humans provide the behavioral elements of performance? Human performance is affected by behavioral, social and psychological circumstances. Determine whether humans will be able to perform as elements of the organizational and social setting which the design hypothesis implies.

o Is the HF support structure adequate? Examine the proposed human factors development plan. Question the adequacy of the proposed training, procedures, selection and organizational structure. Will they support people in performance of the function as required?

o Is cognitive support adequate? Refer to Subsection 4.4, and examine the proposed control, display and intelligence provisions. Determine whether they will meet human needs for information.

3.3.5.4 Are the Three Design Hypotheses Mutually Optimal? A final question concerns whether the engineering, AOF and HF hypotheses are mutually optimal. Ask these four questions:

o Do they meet all requirements? Check to be certain that all roles and tasks are actually going to be performed either by humans or by machines.

o Do hypotheses work together? Check again to ensure that the three hypotheses are mutually compatible and will work together.

o Is their cost/value effective? Check whether the engineering hypothesis implies an excessive cost for equipment or development. Check whether the HF hypothesis will require humans to perform tasks better performed by machines.

o Is the design hypothesis consistent with other hypotheses? Finally, ask concerning the design hypothesis as a whole - is it reasonably consistent with other, previously defined hypotheses in form, cost, level of technology and human/machine balance? All functions should exercise a reasonably consistent level of technology unless there is a clear reason for variation. The role of man should be consistent. Engineering hypotheses should exercise a coherent group of technologies - not, for instance, unnecessarily mixing electrical and hydraulic control. Similarly the HF hypotheses should use reasonably consistent human resource strategies.

3.3.5.5 Closure. If these tests are met, the HF hypothesis and the design hypothesis as a whole are complete for one function. Go back to step 2.1, and develop a design hypothesis for the next function.

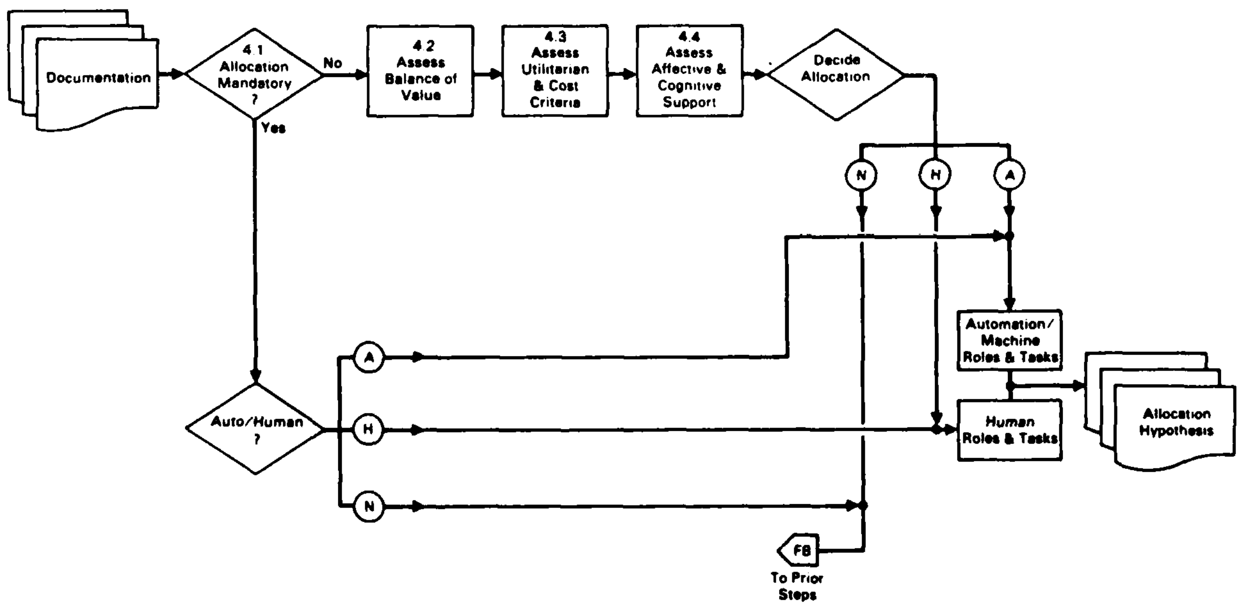
SECTION 4

CRITERIA FOR ALLOCATION OF FUNCTIONS

This section provides four sets of criteria for determining the allocation of functions (AOF). These criteria apply to functions, roles or tasks and are to be applied in making design decisions wherever a choice is to be made between humans and machines, or automation. These criteria apply particularly to the allocation step of subsection 3.3, and the test and evaluation step of subsection 2.5.

The four subsections which follow each treat one set of criteria. Exhibit 4 shows how they are related, and a procedure by which they can be used. This is not an artificial procedure, but a formalization of processes used by successful designers. These four criterion steps are outlined below, and are then each treated by a separate subsection.

Exhibit 4
Applying Criteria For Allocation Functions



Step 4.1 - Mandatory Allocation

Data from the design documentation base supports this process, and when the criteria are applied in the allocation of functions step (3.2) entry is from the engineering hypothesis (3.1). This first step deals with functions, roles or tasks for which no real judgment is required because there are mandatory reasons for allocation. Included are cases in which the required performance is clearly beyond either human or machine capability, or allocation is predetermined by legal or policy constraints.

Three outcomes may occur: (1) Allocation to automation or machine (A) may be mandatory, as in the case of high speed computation. (2) Allocation to humans (H) may be mandatory, as in the case of policy control. (3) There may be no acceptable allocation (N) if (a) automation is mandatory but no feasible technology exists, or (b) humans are mandatory but demands exceed human capability. This is a common situation in design; when no acceptable allocation exists, the function or requirement must be redefined.

Step 4.2 - Assess Balance of Value

If there are no mandatory reasons for allocation, the next most important criterion is the relative effectiveness of humans versus machines. This step provides for systematic assessment of that effectiveness. It provides the primary basis for decision, but is conditional on the outcomes of the next two steps.

Step 4.3 - Utilitarian and Cost Considerations

This step recognizes that once a human operator is present and paid for, he or she can be assigned tasks which otherwise might be given to machines. Aside from this utilitarian consideration, the relative costs of humans versus machines must be considered, and can overrule the step 4.2 balance of value decision.

Step 4.4 - Affective and Cognitive Support

Aside from their effectiveness in performing tasks, humans have unique requirements which must be met. These fall in two categories - the affective group, which includes human psychological and social demands, and the cognitive group, which includes the need of humans for information upon which to act.

Decision

The evaluations of steps 4.2, 4.3 and 4.4 must be weighed and a decision made for the allocation of each function, role or task. When combined with the mandatory decisions of 4.1, three outcomes are possible:

- Automation (A). Functions, roles or tasks are allocated to automation or machines, and define a requirement for further engineering development.

- Humans (H). Others are allocated to human performance, and they define a requirement for the human factors development plan.

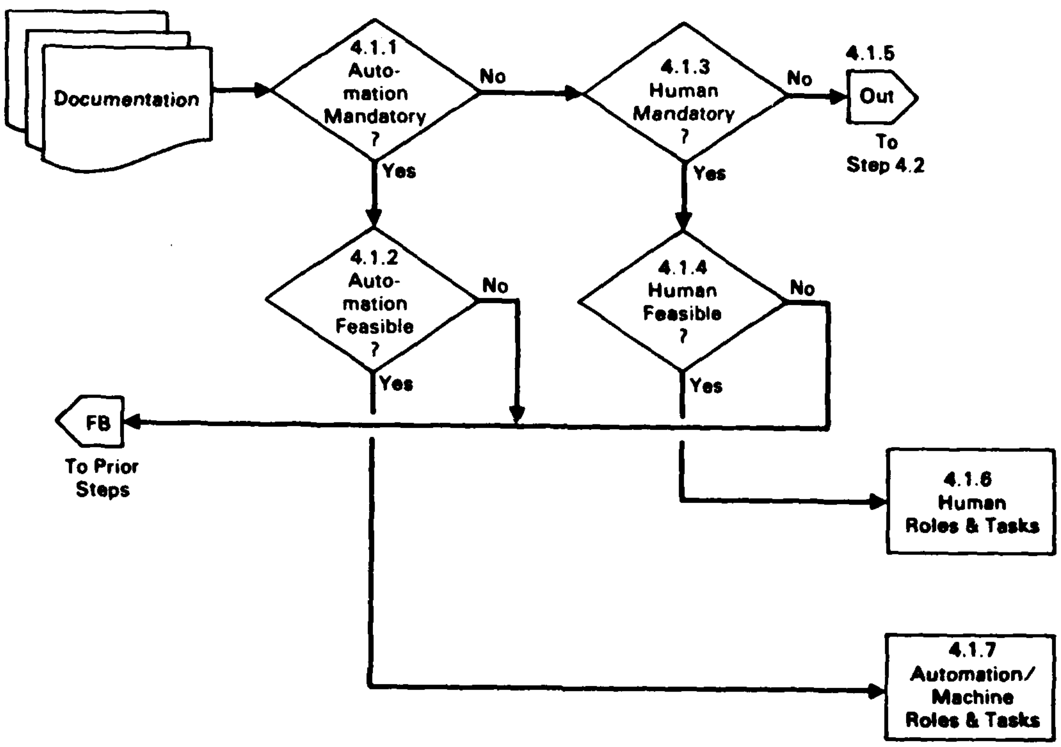
- No Outcome (N). Some functions, roles or tasks may have no acceptable allocation. The presumption is that prior steps in the design logic were defective, or that requirements as defined are not achievable. Feedback to prior steps is indicated.

Now subsections 4.1 through 4.2 will describe these four sets of decision criteria in detail.

4.1 MANDATORY ALLOCATION

This subsection treats the first decision shown on Exhibit 4, at which we identify mandatory conditions for allocation. This step is usually taken intuitively, but is essential to the allocation logic. Exhibit 4.1 shows the four included decisions which the step implies.

Exhibit 4.1
Criteria For Evaluation



4.1.1 Is Automation Mandatory?

Automation (or machine performance) may be mandatory if:

o Working Conditions are hostile to humans because of heat, cold, radiation, noise, pressure, toxicity, vibration, acceleration, insufficient pressure or insufficient oxygen.

o Regulation, law or policy requires automation, as in the case of certain alarms and safety sequences.

- Safety of the System requires an automatic response.

- Tasks are beyond human capability because of response time, perceptual requirements or complexity.

- Hazards to health or welfare are unacceptable.

- Requirements specify automation, as in the engineering concept, role-of-man statement, or design constraints.

If automation is mandatory, go to step 4.1.2. If not mandatory, go to step 4.1.3.

4.1.2 Is Automation Feasible?

Cases exist in which automation is required but is not technically feasible. Automation is not feasible if:

- No Feasible Engineering Strategy is known.

- Costs of an automated solution are clearly unacceptable.

- Time required for development or delivery is clearly unacceptable.

- Reliability of an automated solution will not meet criteria.

- Human Operators will not accept an automated solution.

If automation is achievable, this validates step 4.1.1. Record a mandatory allocation in output block 4.1.7, the list of machine tasks. If not feasible, return by feedback to prior steps of design.

4.1.3 Is Human Performance Mandatory?

This step is the counterpart of step 4.1.1, now asking whether human performance is mandatory. Human performance is mandatory if:

- Labor Agreement reserves roles or tasks to humans.

- Policy-Level Control is introduced into the system by a function, role or task. Human users, commanders, and system owners must be able to exercise policy direction and on/off control.

If human performance is mandatory, go to step 4.1.4. If not mandatory, exit this task at 4.1.5.

4.1.4 Is Human Performance Feasible?

Cases exist in which human performance would be required, but cannot actually be achieved or provided. This step is a step frequently not taken, with the result that the end system is at some point not effective because humans are not able to perform as required. Human performance is not feasible if:

- The Human Limitations listed in step 4.1.1 apply.
- Human Costs would clearly be unacceptable.
- Human Reliability will not meet functional requirements.

If human performance is achievable, this validates step 4.1.3. Record an allocation to human performance in the list of human roles and tasks, block 4.1.6. If not feasible, return by feedback to prior steps of the design logic.

4.1.5 Unallocated Functions

Functions, roles and tasks for which an allocation is not mandatory either to automation or to humans exit this step to step 4.2.

4.2 BALANCE OF VALUE ALLOCATION OF FUNCTIONS

This subsection describes the major criterion by which functions are allocated, which is the operational merits of automation versus human control. This criterion (Exhibit 4 step 4.2) applies when there is no mandatory reason for allocation, and will normally result in an allocation decision, but that decision may be overruled by steps 4.3 or 4.4, which treat cost and human acceptance criteria.

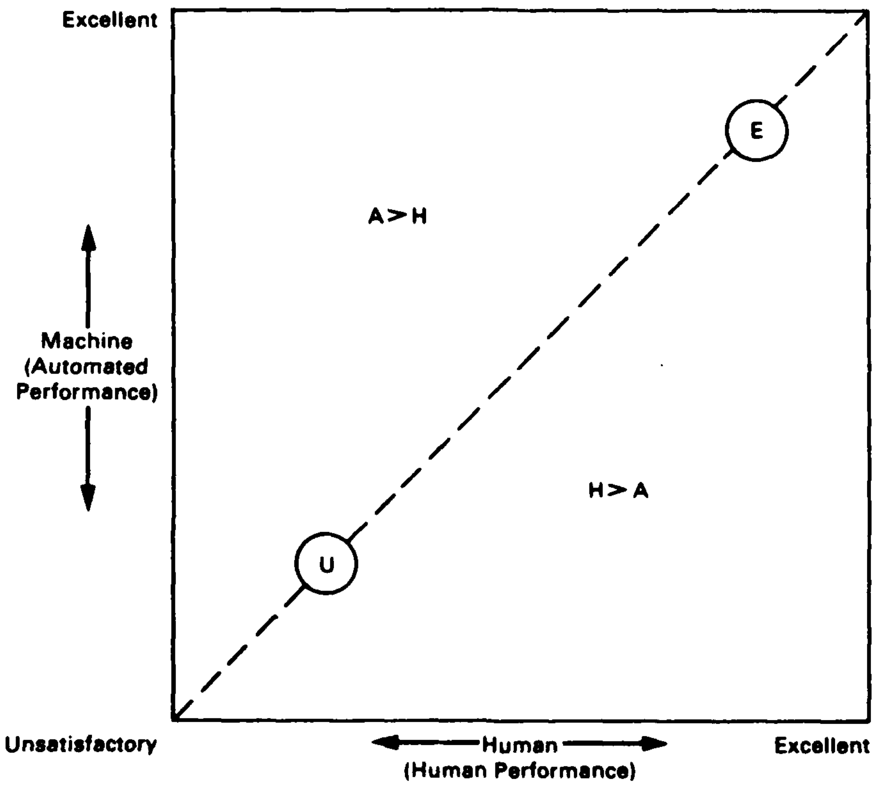
The fact that humans perform a task poorly does not necessarily ensure that machines can perform it well. In this subsection we present a decision matrix, the use of which will clarify the operational conditions which can exist in comparing the merits of humans versus automation, and the consequences of those conditions.

4.2.1 Decision Space.

Exibit 4.2A represents a decision space in which the X axis is the operational merit of humans, scaled from "unacceptable" to "excellent," and the Y axis represents the corresponding merit of automation, considering the technology available. The X and Y values of a point in that space will represent the estimated relative predicted effectiveness of automation versus humans in performing a function, role or task.

"Merit" in this context is a complex value and must be an engineering or a human factors estimate; nevertheless, design judgment rests on such estimates, with or without use of this matrix. The elements of merit include effectiveness, speed, reliability and availability of technology, depending on the function concerned. Within the matrix are two major areas, delineated by the dotted line. Any function which falls into the upper left triangle is predicted to be better performed by automation. Any function in the lower right is better performed by humans. Cases which fall on the dividing line are predicted to be performed equally well by humans or by automation; however, those at the lower left near the area marked "U" will be performed poorly, while those at the upper right near the area marked "E" will be performed excellently.

Exhibit 4.2A
Decision Space For Relative Control
Performance Of Human And Machine



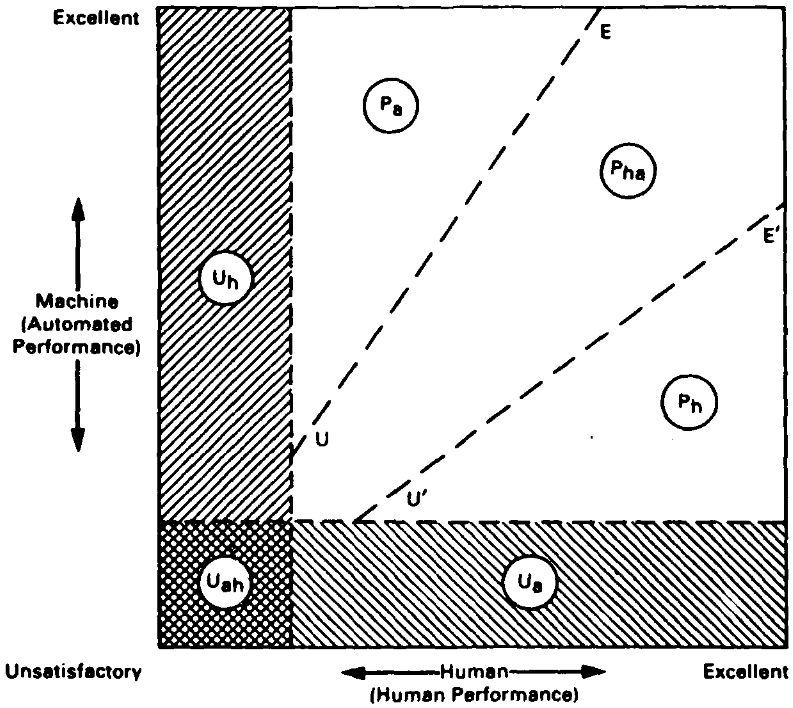
4.2.2 Decision Matrix

Exhibit 4.2B provides a more useful delineation of zones within the decision space. Six zones are differentiated. Each represents a set of cases which should be treated differently. Six rules apply:

- o Region Uh - Unacceptable - Human. Functions which classify in this area (far left, shaded) are predicted to be performed very poorly by humans. These functions should presumably be allocated to automation.

- o Region Ua - Unacceptable - Automation. Functions which classify in this area (bottom, shaded) are predicted to be performed very poorly by automation. They should presumably be allocated to human control.

Exhibit 4.2B
Decision Matrix For Allocation Of Functions



o <u>Region Uah - Unacceptable-Automation and Human</u>. The region at which Uh and Ua intersect (lower left, heavy shading) is a special case. Functions which classify in this area are performed so poorly, either by automation or by humans, that they should be avoided altogether. These functions represent infeasible design, and should be returned by feedback for reconsideration at prior steps of the design logic.

o <u>Region Pa - Preferred Automation</u>. Functions which fall in the unshaded region at the upper left might be performed acceptably by humans, but automation is preferred. In general, such functions will be allocated to automation. There are exceptions: (1) Humans may be selected for reasons of cost. Normally this decision will be made during the next major step, step 4.3. (2) Humans may be selected for reasons of affective or cognitive support. Normally this decision will be made during step 4.4. On the other hand, if it is clear that cost or human considerations will prevail, that decision should be made at once.

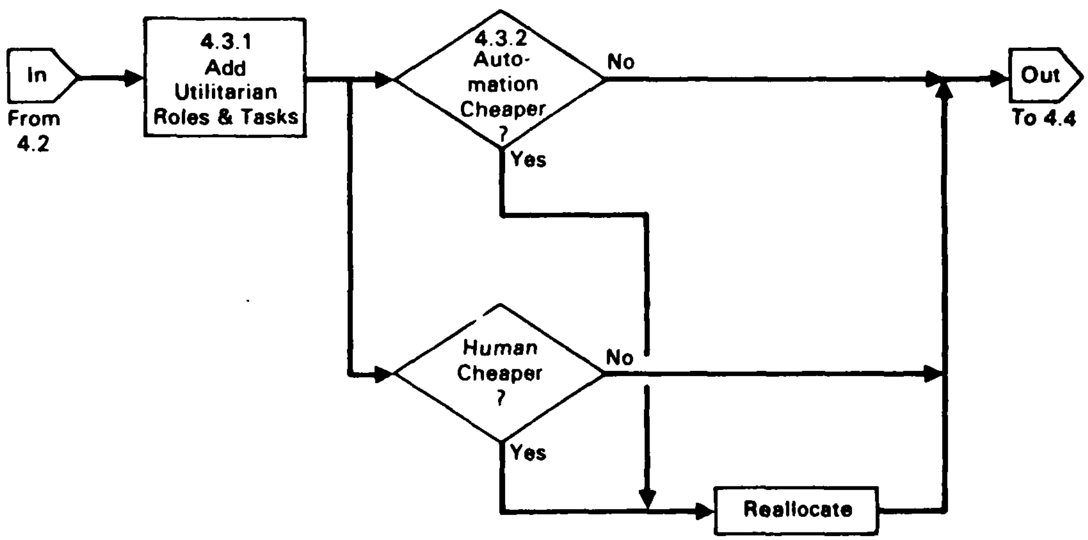
o <u>Region Ph - Preferred Human</u>. Functions which fall in the unshaded region at the lower left might be performed acceptably by automation, but human control is clearly preferred. These functions will normally be allocated to human control. Exceptions exist as before: (1) Automation may be selected to save costs, or to save crew weight. (2) Automation may be selected to prevent human overload. These decisions may either be imposed later at steps 4.3 and 4.4, or they can be made now.

o <u>Region Pha - Preferred Human or Automation</u>. Finally, there is a central region representing those functions which will be performed about equally well either by humans or by automation. Functions which classify in this region can be allocated either way. Normally, the considerations of 4.3 and 4.4 will assist in making an optimal allocation, but it will not be improper to allocate on the basis of convenience. The design team can select an option for whatever reason they favor.

4.3 UTILITARIAN AND COST CONSIDERATIONS

This is the point at which cost is considered. In effect, the design team is reviewing an allocation which has been provisionally made at step 4.2. That allocation may now be modified or overruled in a two-step procedure: First, we assure that where people are present and paid for, they are fully utilized. Then we perform an informal cost/value analysis focusing on the balance between people and automation. Refer to Exhibit 4.3.

Exhibit 4.3
Utilitarian And Cost Considerations



4.3.1 <u>Add Utilitarian Roles/Tasks</u>

Where humans are present in the system, paid for, and not fully employed, we should use them if possible. At this step we identify functions, roles or tasks which are otherwise assigned to automation, and assign them to humans to minimize cost and complexity. In the process we will contribute to cognitive support and perhaps job satisfaction. "Cognitive support" refers to deliberately planned human activity which keeps the human operator active and informed about the system state. Cognitive support and job satisfaction will be treated in detail by step 4.4.

This step examines functions which have been provisionally allocated, and identifies control requirements which can be reallocated to humans for three reasons: (1) To save automation costs (the primary goal). (2) To contribute to cognitive support. (3) To contribute to job satisfaction.

4.3.1.1 Is an Operator Available? First the designers determine whether there is a human present at the point represented by the function. If humans are present, qualified and not overloaded already, the designers can consider reallocating some portion of the function to human control.

4.3.1.2 Is the Function a Suitable Candidate? If a human is available, the function is next examined for roles or tasks which meet criteria for re-allocation, as follows:

- Not Demeaning. Tasks which are trivial, demeaning, or would lead to boredom should not be reallocated.

- Not Too Difficult. Tasks which would lead to cognitive overload or increase probability of error should not be reallocated to humans.

- Matrix Position. Roles or tasks reallocated should classify in the upper right of region Pha, on the decision matrix in Subsection 4.2. They should be tasks suitable either for humans or automation, tasks which can be well performed by either one.

4.3.2 Cost-Balance Consideration.

This step considers how system cost will be affected by the allocation of a function. One objective of automation is to minimize cost. This means investing in automation when it reduces the need for manpower or for expensive levels of skill or training. It also means not investing if automation will cost more than the people it replaces. To make this judgment, the designers use whatever cost estimating machinery is in place on the project, adapting it to this assessment. In the absence of such resources they will use expert judgment, and they will ask one of two opposing questions:

- Is Automation Cheaper? If the function is provisionally allocated to human control, they ask whether automation could reduce overall system cost. They consider what automation assets are forecast to be available in the system. If automation can reduce costs and there are no compelling reasons for manual control, the function will be allocated to automation.

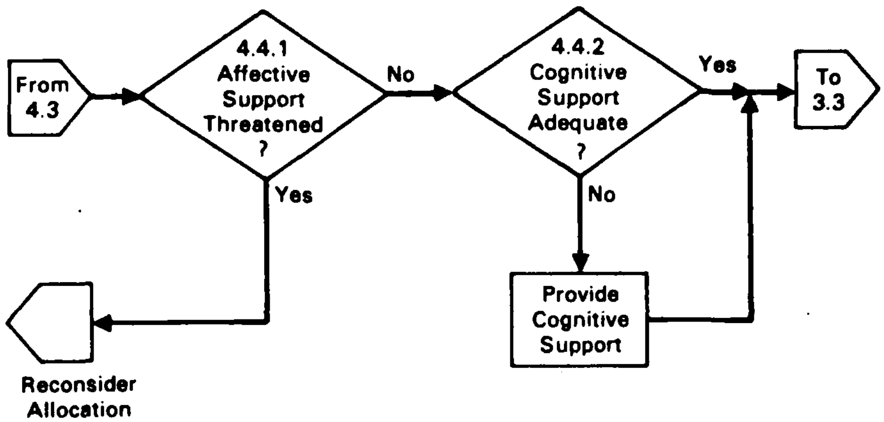
- Is Human Control Cheaper? If the function is provisionally allocated to automation, they ask whether human control could be cheaper. If so, and if there is no compelling reason for automation, the function is allocated to human control.

The output of these decisions is a provisional allocation for the function concerned, subject to final reconsideration at step 4.4.

4.4 ASSESS AFFECTIVE AND COGNITIVE SUPPORT

This subsection offers a final criterion by which the designers consider what we will call "affective and cognitive support." Earlier steps treated the human operator as a machine component. They considered only the ability to perform roles and tasks, and did not consider some uniquely human characterisitics which can limit human performance. The fact that a human can perform a task under one set of conditions does not assure that he or she will do so under all conditions. In fact, humans are notable for their unreliable performance when deprived of two kinds of support. The first is intellectual. It is the supply of information which is needed to support decisions, and we call it "cognitive support." The second is psychological and psychosocial, and is a more familiar issue. We call it "affective support" and we will treat it first (Exhibit 4.4).

Exhibit 4.4
Affective And Cognitive Support



4.4.1 Affective Support

Affective support is provided by systems and organizations which are designed to meet the psychological and emotional requirements of people. These are too numerous to list here, but they include the human need to be challenged in a non-threatening way, but at a level appropriate to personal abilities. People need to feel that their work is valued, that they are personally secure and on an appropriate career path, and that they are in control of things which concern them. These issues are the concern of industrial and organizational psychologists. At this point the developing human subsystem must be evaluated by such professionals to determine whether it will be one in which people will work effectively. If the function being considered may adversely affect affective support, it should be considered for reallocation.

4.4.2 Cognitive Support

Cognitive support is a more specifically machine-related human need, and is especially important in automated systems, because those systems frequently deprive humans of needed information, or of meaningful activity.

4.4.2.1 Mental Models. A key concept is that of mental models. As a human learns his tasks, he (or she) develops a mental representation of the system, its dynamics and its behavior. Each time he observes the system or reads instruments, he refines his mental model. He uses it to understand what is happening, and to predict what the system will do. He uses it to forecast the consequences of control interventions, and to plan control actions accordingly. The better the model, the better he will recognize abnormalities, anticipate actions, and control the system. A major objective of system design is to ensure that each operator is both able, and forced by his duties, to maintain a mental model which can support any decision he will be required to make.

4.4.2.2 Effects of Allocation to Machine. When a function is allocated to automation, the operator or crew may be deprived of information concerning the events which are automated. This creates a requirement for specific means to (1) display the needed information, and (2) ensure that operators will assimilate it. This is a crucial issue in allocation of functions.

Even if instrumentation is totally adequate, the operator or crew may not notice, may not remember, or may not integrate observed data into the model. If on the other hand the operator must personally decide and act, he (or she) is automatically forced to update the mental model. If he is active in control, his model will become progressively more detailed, accurate and finely calibrated. In contrast when humans are out of the control loop and not active they lose control of the model. Humans are not good at monitoring tasks. In the monitoring role they learn more slowly, attend unreliably, and are less satisfied with their work.

4.4.2.3 Evaluate Cognitive Support. If the function under consideration has been allocated to automation, we must determine whether humans will be deprived of information as a result. The following questions should be asked:

- Is Instrumentation Adequate? Do the instrument displays and other sources provide all the information which humans may require for normal performance and emergencies? Does the arrangement of displays reflect appropriate priorities?

- Are Humans Active? Displays by themselves are not adequate. Does the work sequence involve the operator so that he must acquire and maintain an adequate mental model? Will the model be updated regularly enough?

- Is the Level of Activity Adequate? Are humans provided sufficient activity that they must remain alert? Is the activity of sufficient interest and difficulty to force alertness?

- Is Confidence Maintained? Does the level of information provide confidence? People need: (1) A certain amount of redundancy in key data. (2) A level of detail and precision slightly greater than that actually required for decisions. If these are not provided, people may lack confidence in the data.

4.4.2.4 Closure. If the provisional allocation to automation does not meet these tests, revise the allocation of roles and tasks appropriately. Completion of this step (4.4) provides a completed allocation hypothesis.

SECTION 5

HUMAN-MACHINE MODELS

This section presents some models of the human-machine system. They show the connectivity of elements within both the machine and the human operator, the elements of the control loop, how that loop can be configured, and the sequences in which parts interact. These models are "formal" in that they show form, rather than quantity. They are chosen from the literature, and are representative of the many models which that literature offers.

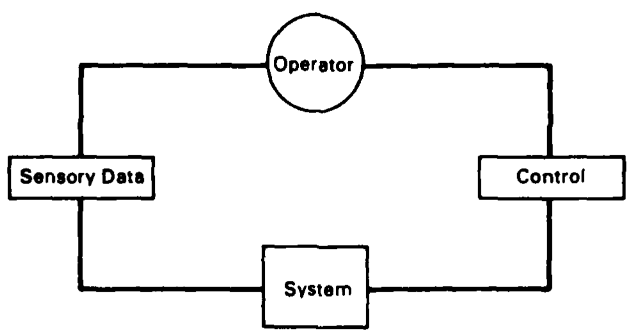
These models can be useful in two ways. First, they can clarify the basic nature of the control process and the relationship between systems and humans as controllers or decision makers. Second, they can be used analytically to identify the sequential information processing steps which take place in systems control. In the machine those steps are performed by specific components or software commands. In humans they are performed by specific organic subsystems, but we know much less about human subsystems than about those of machines. We will refer to the information processing steps as "elements of performance." Mission success depends on successful performance of those elements, whether they occur in the human or in the machine. To secure a good allocation of functions we must assure that each element can meet conditions of the control requirement, and that the elements available from humans and from machines are fully exploited.

In this section we will first show two elementary models, to assist those readers who are not familiar with human-machine modeling. Then in three subsections we will present three categories of models which can be applied to the analysis of human-machine design.

The General Model

Exhibit 5A illustrates the basic relationship between a human and a machine. Simple as it is, all other models are derived from this one. The operator acts to control the machine; through sensors he or she observes the

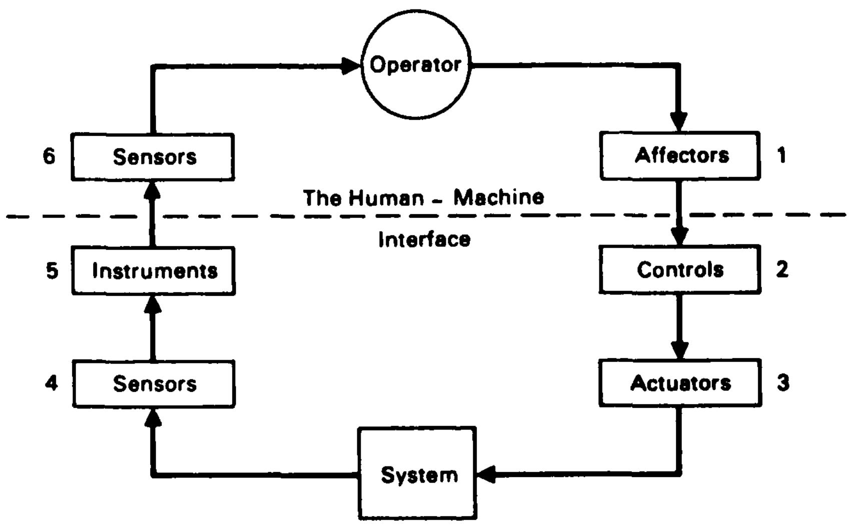
Exhibit 5A
General Model Of Control



behavior of the machine, and the results of control actions. He or she provides feedback through control action, either to stabilize the machine in a desired state, or to move into new steps of a task. This model describes all mechanical work, including the simplest tool behaviors.

The model of Exhibit 5B shows additional elements of the control cycle, as follows. The operator acts through organic affectors (1) - hands, feet, or voice. Those actions are taken, in most cases, through controls (2). The controls, in turn, act through actuators (3), the affectors within the system. States and events within the system are detected by sensors (4), which display that information through instruments (5). The operator acquires information selectively from instruments, through organic sensors - eyes, ears, touch (6). The human-machine interface can be seen to lie between the sensors and affectors of the operator, and the controls and displays of the machine. The elements shown here will reappear, with expanded detail, in models which will follow.

Exhibit 5B
Detailed General Model Of Control



Categorization of Models

The following three subsections each deal with one category of model, as follows:

o Levels of Automation. Subsection 5.1 offers four simple models which illustrate the hierarchical relationships between operator and system. These models show linkages, the subordination of control loops, and the delegation of control functions. They illustrate what can be called "levels of automation."

o Elements of Cognition. Subsection 5.2 offers models of information processing within the operator. They can assist with the most difficult task in allocating a function to humans: the analysis of element-by-element cognitive function.

o Elements of Performance. Subsection 5.3 offers models which show additional elements of human performance. The models shown treat the sensory and effector systems, memory, and the affective aspects of human performance.

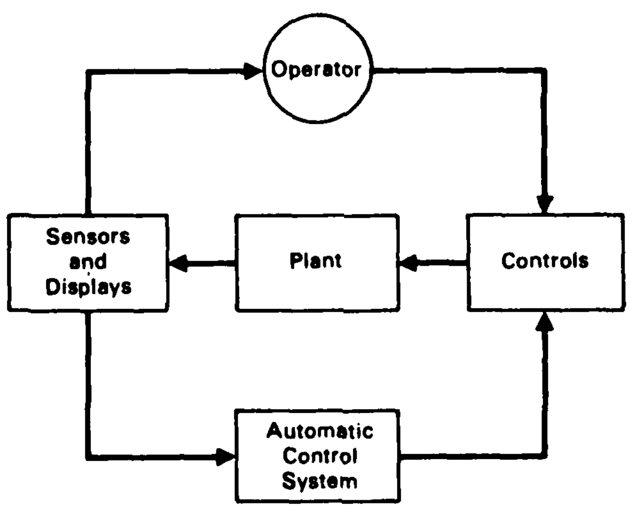
5.1 LEVELS OF AUTOMATION

As often used the term "levels of automation"" has little meaning. There is a level of available technology and a level of investment in technology; there is also a "role of man," as defined in Subsection 2.1. But the only sense in which "level of automation" has meaning is in describing the hierarchical relationship between operator and machine logic - what humans are required to do or not do, and how they compete with or control elements of an automated system. The models which follow will clarify some of those relationships, and reveal their benefits and hazards.

5.1.1 The Symmetrical Control Model.

Exhibit 5.1A represents the elements of a system and its automatic control system, a hypothetical case in which automation and the human operator are assigned symmetrical roles. The system (in the center) is governed by controls at the right, and its state is observable through sensors on the left. The operator (above) receives information from the displays, and responds with control actions. The consequences of control actions are observed through the displays in a continuous feedback loop. In a symmetrical way, an automatic control system senses system status and affects control.

Exhibit 5.1A
The Symmetrical Control Model



A quick analysis shows that this is an unacceptable configuration. The operator and the control system are trying to do the same things, and they are in competition for control of the system. They will sometimes undertake conflicting control strategies. What makes this danger more serious is that neither the operator nor the control system can act on the basis of complete information, since neither knows what the other is planning to do. Either can independently change the configuration of the system; neither can conduct a coherent control strategy.

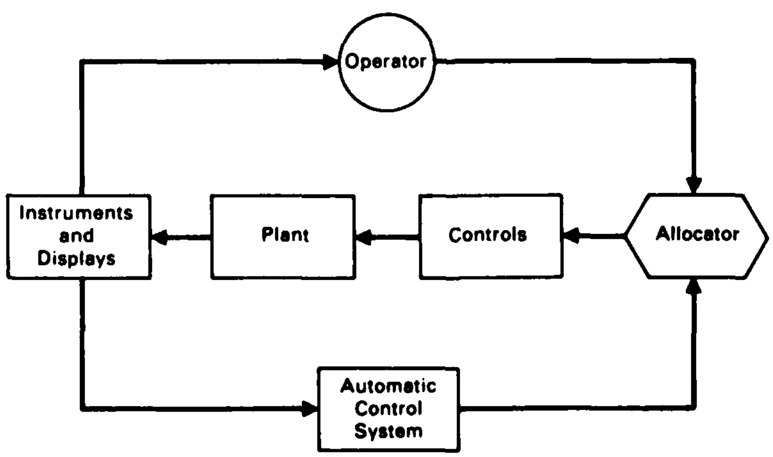
This illustrates that functions must be specifically allocated. It also shows that the operator and the automated system must each be informed about the state of the other. The operator must know what automation will do, and the system logic must "know" what the operator will do.

No system is actually built as shown in Exhibit 5.1A, at least not altogether. It does frequently happen that single functions are allocated so that automation and human operators must compete for control, or can initiate competing control strategies. This has been the underlying cause for several recent technological disasters. It is vital that functional analysis should detect such potential conflicts, and prevent them by specifically allocating functions to humans or to automation.

5.1.2 An "Allocated" Model

We might attempt to correct the defects of the previous model by providing a programmed division of tasks. Exhibit 5.1B illustrates such a system, in which an "allocator" exercises a predetermined rule or program, to apportion tasks between the operator and automation. Allocation might be determined by function (e.g., human controls weapons release, automation controls weapons platform), or it might be determined control by control (e.g., operator controls switch A, automation controls switch B). In either case, human and machine can no longer oppose each other's actions. This

Exhibit 5.1B
An "Allocated" Model



configuration might be used with caution, but never in high level system control.

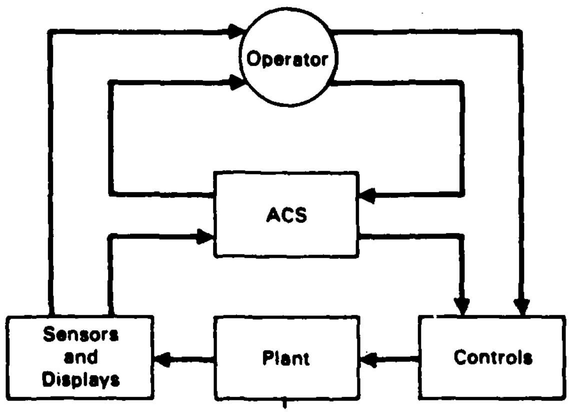
First, notice that this is what happens when we use a servosystem or a set-point controller. We offer the initial decision to the operator and all subsequent decisions to the machine. This is acceptable as a means of delegating detailed, repetitive, or high speed-of-response tasks to automation, so long as initiation and policy direction remain under human control.

Second, notice that this configuration should be imposed only when we have thought the functions out completely, and are willing to accept the consequences that under defined conditions automation will preempt human control. For instance we might accept automatic seat ejection which the pilot cannot override. In general, this kind of control is imposed for safety reasons or to preclude individuals from misusing the system. But for the most significant control functions this configuration is not satisfactory. It does not meet the basic condition that humans, not machines, must exercise ultimate control and decide what to do or not do. Moreover, we want to maximize the number of options available to the operator, so that he or she can respond to unpredictable conditions with unpredictable strategies. That is one of the major advantages of having humans in the system.

5.1.3 A Hierarchical Control System

Exhibit 5.1C illustrates a control system in which the automation loop always lies within an outer, human-driven loop, where it can be observed and overriden by the operator. This model represents a system in which the inner, automation-driven loop controls either (1) certain predetermined functions, or (2) the whole system under normal conditions. In either case, the operator in the outer loop is able to control directly if he or she wishes. In addition there is a third operator-to-control system loop, which enables the operator to direct selectively whether automation will exercise control of any particular function.

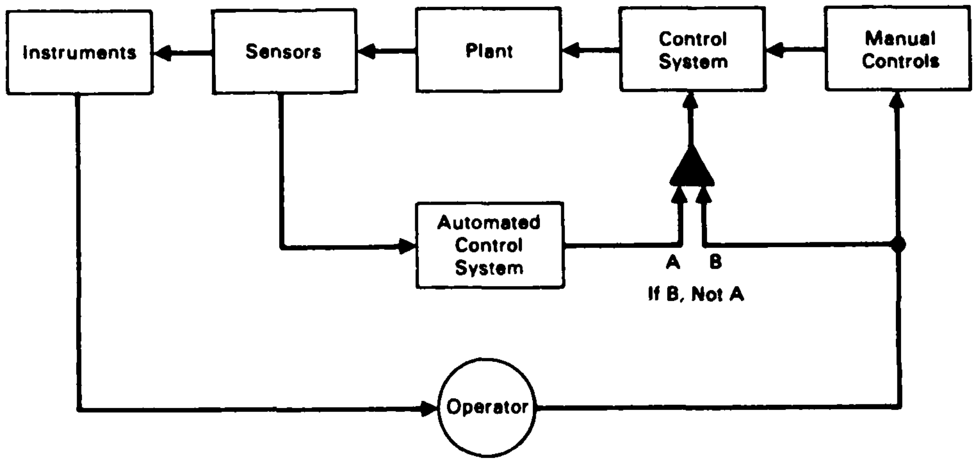
Exhibit 5.1C
A Hierarchical Control System



5.1.4 Operator Override Capability

The objectives of paragraph 5.1.3 are met by the configuration of Exhibit 5.1D, which is a more realistic illustration of how such objectives are met in actual systems. In this model, the system is normally controlled by the automatic control system in the center. The operator is outside, in the primary control loop. If the operator chooses to intervene, he or she can do so control by control, and the initiation of any manual control will override actions of the automatic control system.

Exhibit 5.1D
Humans Outside The Control Loop



5.2 ELEMENTS OF COGNITION

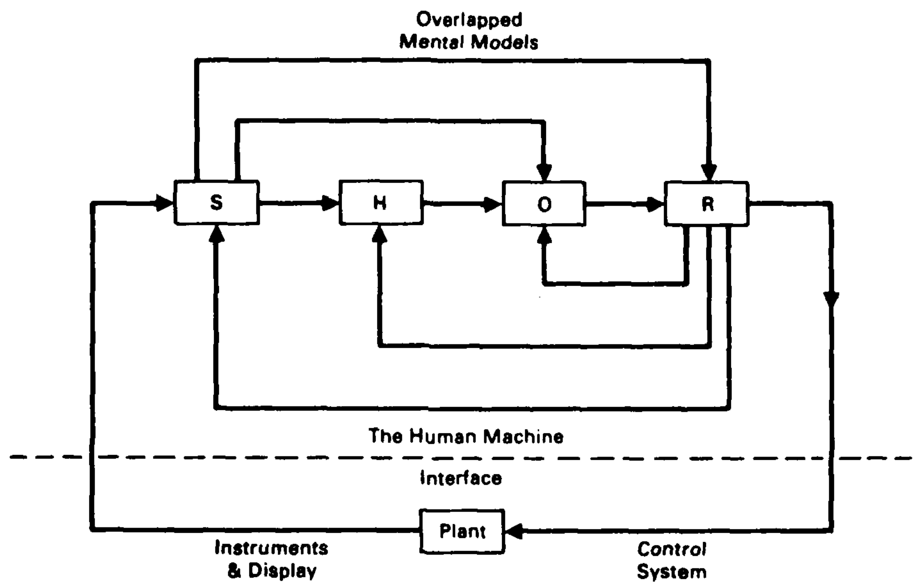
This subsection examines the human-machine control loop in further detail, to identify some elements of human cognition. The four models shown here identify sequential information processing steps which take place within the central nervous system of the operator, as those steps are generally understood. Successful control depends on the accomplishment of each cognitive processing step, steps which can be called the "elements of cognition." Those elements can be viewed as gates, filters, transmission paths and storage sites within the human operator, who for purposes of this subsection can be viewed very much as a computer or an automatic control device. Successful design will depend on functions which do not exceed the capacities or other limits of each element of cognition. It will also depend on fully utilizing the capabilities which those elements can provide.

These four models may appear different in structure and in the taxonomy of elements which they include. Actually they are not in conflict, but represent differences in emphasis. All are equally valid, and all represent accepted principles of human factors science. Users should select a model depending on the function under analysis, and employ whichever model proves most useful.

5.2.1 The SHOR Model

Exhibit 5.2A is a rendition of a model by Wohl (1981). It is described as a control-theoretic approach, in which there is a physical domain represented by the system (plant) dynamics, plus the instrumentation and control systems. On the other side of the human-machine interface is a human information processing domain. Wohl identifies four main areas in this domain as follows: Stimulus (S), or information organization; hypothesis (H) generation and selection, which provides an analysis of the situation and its meaning: option (O) generation and selection; and finally response (R) organization and execution.

Exhibit 5.2A
The SHOR Model (From Wohl, 1981)



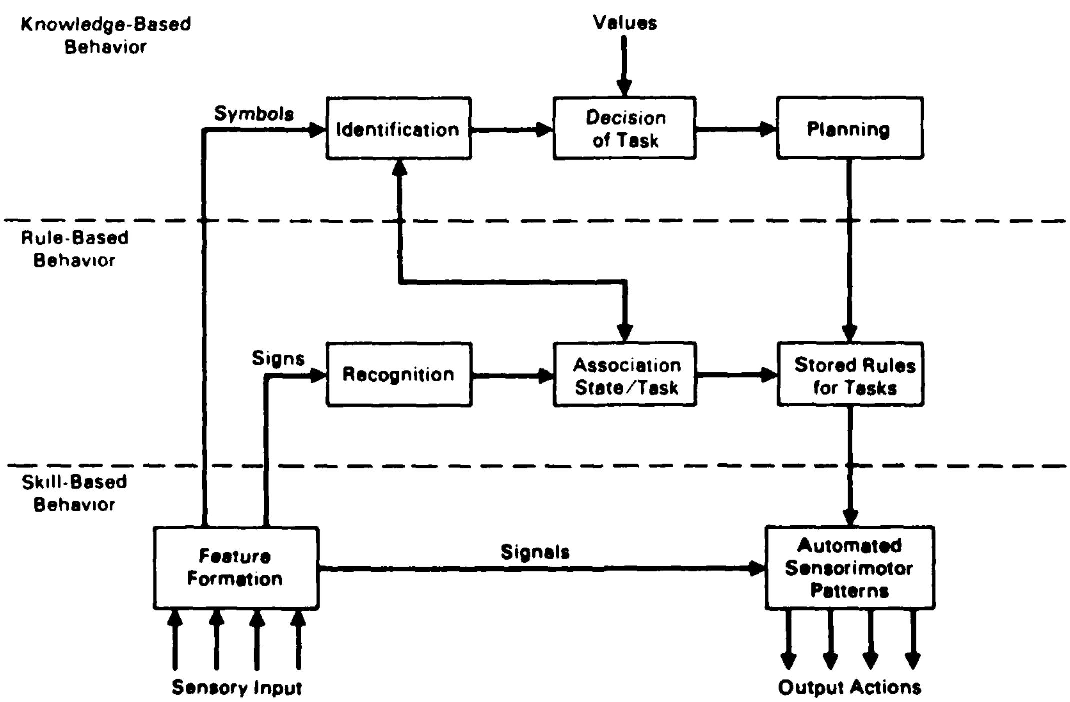
The measurement system develops and transmits information about the system. This information appears as instrument displays which act as a stimulus to the human operator. The operator maintains a mental model of how the plant works. Based on the model and on the instrument readings, the operator forms a hypothesis about the state of the plant, including a prediction of its future behavior. He mentally explores the consequences of control actions, and selects an option consistent with his hypothesis and the system indications. If these indications remain consistent, he will carry out the selected option, which will affect the system dynamics and initiate an iteration of the SHOR cycle.

The name SHOR model reflects its elements of stimulus, hypothesis, options and response. The operator's mental model can support several overlapping hypotheses at any time. Note also the multiple internal paths by which a response can be selected and organized.

5.2.2 Levels of Human Behavior

It may be useful to differentiate control functions as requiring the exercise of the three levels of control behavior identified by Rasmussen (1980). Exhibit 5.2B is derived from Rasmussen's model, and is a map of several paths which a control decision may take during the cognitive control process. At the bottom are skill-based actions, which require high levels of training and which include both purely motor skills and the stimulus-response behaviors of the psychologist's "well trained subjects." At the second level are rule-based behaviors, in which responses can be more flexible and are formulated by the conscious application of learned situational rules. The situation is recognized, associated with a set of rules, and the performance required by the rules is initiated. Finally at the top level are knowledge-based behaviors which provide the capability to respond to unfamiliar situations. The operator identifies a situation and analyzes it on the basis of mental models and a general knowledge of machine behavior. He then plans and executes rules to perform a task.

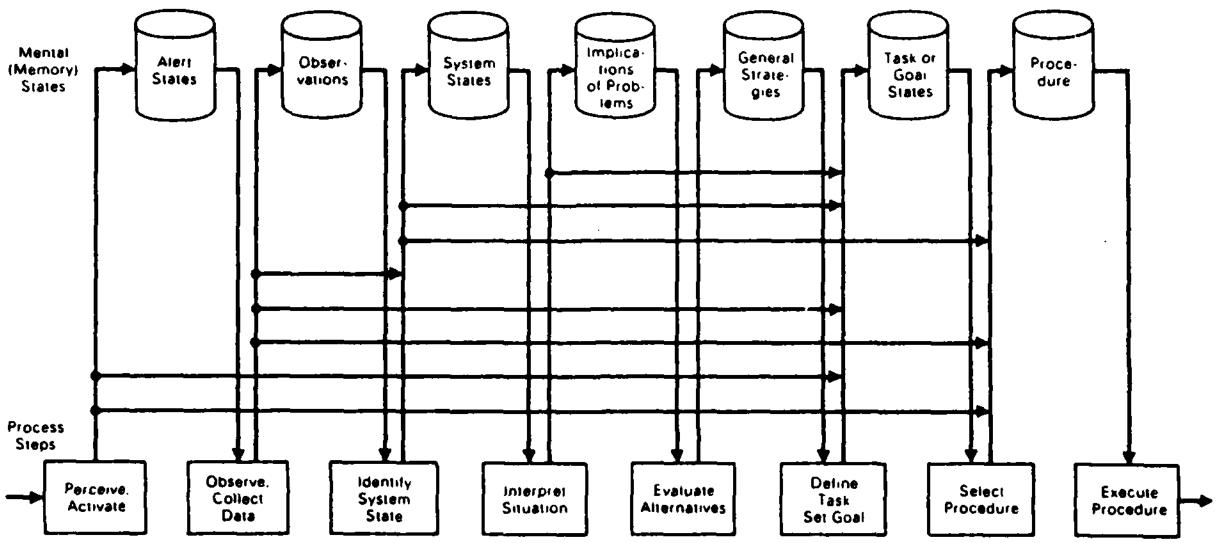
Exhibit 5.2B
Cognitive Levels Of Human Behavior
(From Rasmussen, 1980)



5.2.3 Temporal Processing Sequences

Derived indirectly from a model by Rasmussen (1980) is that of Exhibit 5.2C, which provides a relatively detailed analysis of the successive steps which a decision may take, and of the mental or memory states which accompany those steps. This was originally published as a ladder-shaped model, with "Evaluate Alternatives" shown as the highest level processing step. The legends should be self explanatory. Note that decision making can require the sequential exercise of all of these steps, or can be shortcut by any of the paths represented by horizontal arrows. These shunt paths have the effect of speeding action and of limiting the load on higher level conscious processing. For instance, the bottom arrow defines a case in which perception is followed by the automatic execution of a learned procedural response.

Exhibit 5.2C
Temporal Processing Sequences
(Adapted from Rasmussen, 1980)



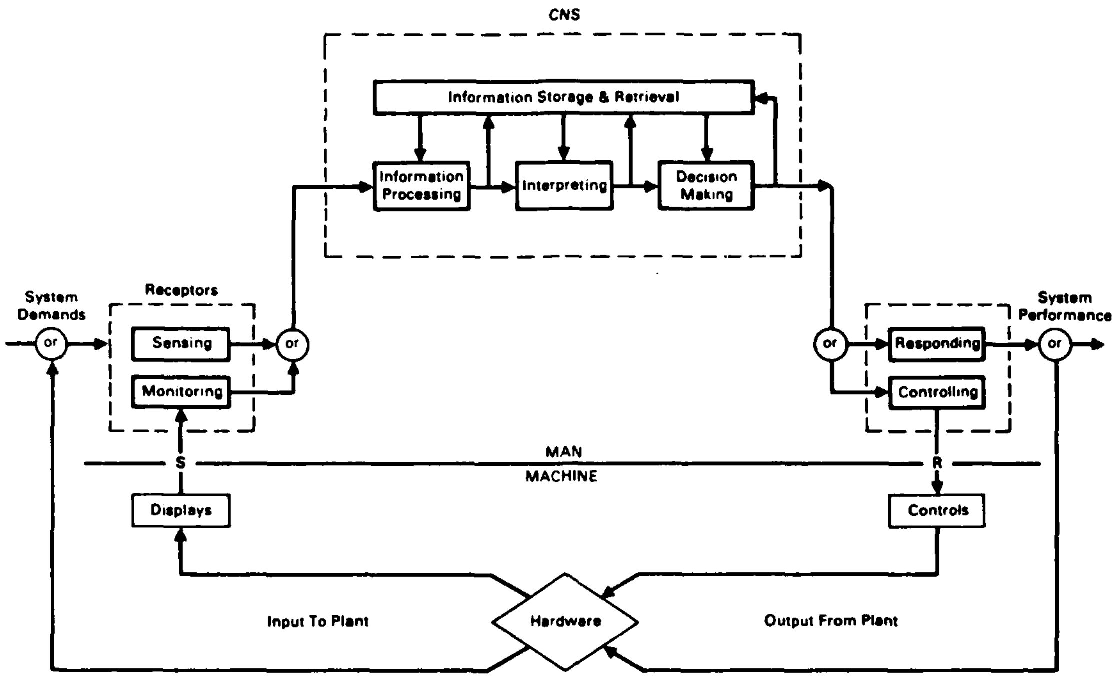
5.2.4 Core Performance Areas

Exhibit 5.2D is a model by Price, Smith and Behan (1964), which provides additional detail of the interfaces between operator, system and environment. The legends are self explanatory except for a few abbreviations: CNS is the central nervous system; S stands for stimulus and R for response. The terms "plant" and "hardware" should be interpreted to mean "system."

5.3 ELEMENTS OF PERFORMANCE

Models in the previous subsection emphasized cognitive processing and treated the human operator as comparable to a control component. But in order to fully evaluate human capabilities in control system design we must recognize the non-cognitive aspects of human performance. These include the input-output functions of sensation, perception and motor control, the storage functions of memory, and the affective aspects of behavior which make it impossible to regard human workers as equivalent to machine components. This

Exhibit 5.2D
Core Performance Areas
(From Price, Smith And Behan, 1964)

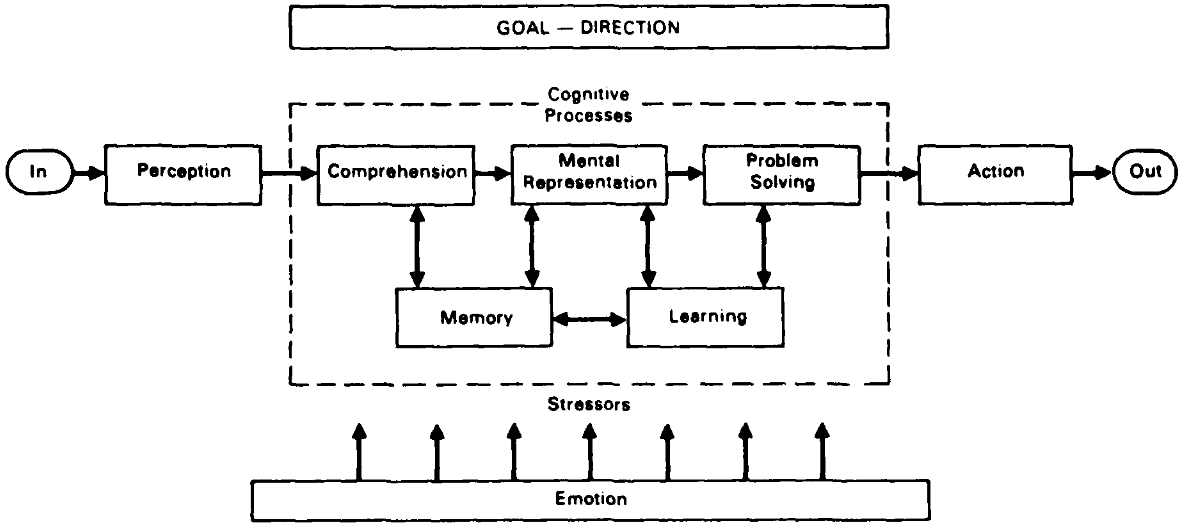


subsection includes four models which show cognitive function, but relate it to input-output, memory and affective elements of performance.

5.3.1 A Global Model

Exhibit 5.3A is a model by Dougherty (1981) which includes each of the elements named above. It is said to be based on a recent survey of cognitive psychology by J. R. Anderson, and represents elements of performance that are well accepted in the literature. Shown here are elements seen before in subsection 5.2: comprehension, mental representation (modeling), problem solving, memory and learning. To make the model complete, Dougherty adds the mechanisms of perception as input and of action as output. These provide the link between cognition and the external system which the operator will control. Goal direction is shown at the top, and provides the motivation for executing the process sequence shown in the center. Emotion is shown at the bottom, as a stressor on the process. This model is globally complete, in that it includes all major elements which are represented in the literature.

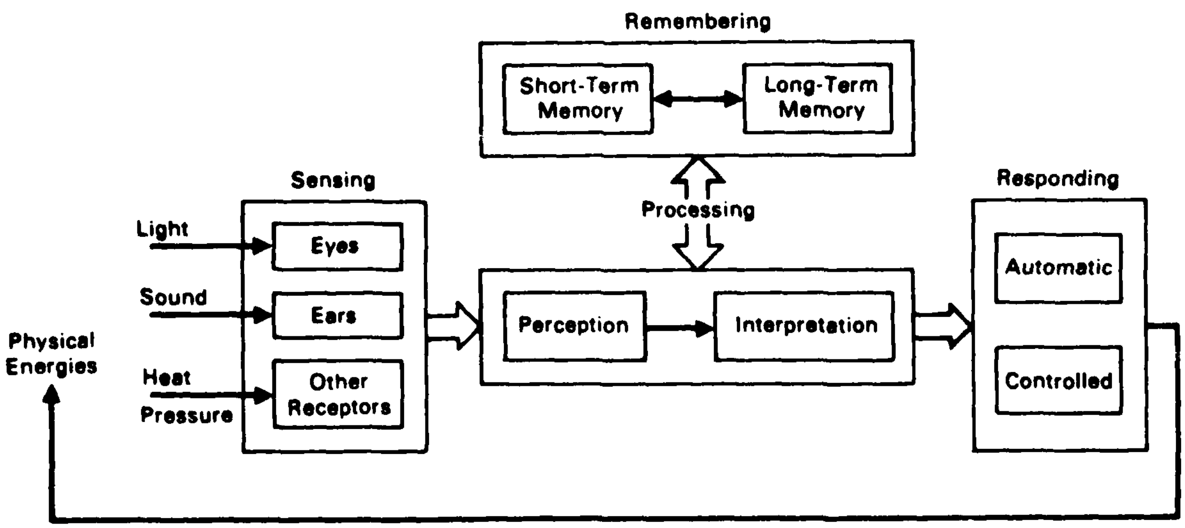
Exhibit 5.3A
A Global Model (From Dougherty, 1981)



5.3.2 Details of Input, Output and Memory

Exhibit 5.3B is a model developed by the Electric Power Research Institute (EPRI, 1982), specifically as a tool for understanding the operators of nuclear power plants. The model is of interest because it illustrates the input-output elements in greater detail, and because it suggests some elements of memory.

Exhibit 5.3B
Details Of Input, Output, And Memory
(From Electric Power Research Institute, 1982)



At the left the sensory system is shown in terms of separate senses leading into perception. Not shown on this or any other widely accepted model is sensory buffer storage. Such storage is considered to exist but has not been the subject of much applied research. Nevertheless, that storage is important in activities such as scanning displays and evaluating operational situations, where what is perceived at one instant is available as a rapidly decaying information store, and may or may not be incorporated into memory. On the right, the output or motor functions are shown and are classified into an automatic and a controlled category. Automatic responses are those which are executed without conscious oversight - the highly learned motor responses which lie on the short processing paths of Exhibit 5.2C.

Of particular value in this model is the separate representation of short-term and long-term memory. Because of its small capacity and high decay rate, short-term memory is a particular concern in control system design. It limits the amount of input information available to support current control actions and the amount of information which can eventually be stored in long-term memory. These limits imply requirements for supporting information displays and for buffer storage at the control position to back up human memory. The user can refer to the HEDB for more information on short-term memory.

5.3.3 Expanded Paracognitive Model.

Exhibit 5.3C is a model by Norman (1981) which offers an expanded illustration of the affective elements of performance in which cognition is embedded. Norman notes that cognition is not the dominating element of human behavior, but is embedded in more primitive processes of the nervous system. These are shown at the top, in overlapping circles. The basic flow of cognition is shown at the bottom, with emphasis on steps of input-output processing - sensory function, sensory memory, pattern recognition in input, and motor program selection, motor control, and effector function in output. The inclusion of speech as an output is significant since that channel is often overlooked, and is important in any situation which requires team interaction or voice communication.

5.3.4 The System Delta

The last model is a general model of work behavior by Pulliam (1981). The features of importance (Exhibit 5.3D) are the representation of changes in external system state, and their corresponding internal representation as mental models, including a model of the driving "system delta."

The worker (1) is shown within a system environment (2), which includes a current (actual) system state (3). The purpose of work is to achieve a desired system state (4). This is true at a global level: build a house, launch a satellite. It is equally true at a micro level: adjust a voltage, saw a board. These changes are accomplished (or attempted) by the worker's manipulation of the environment (5), either directly or through controls. Work is performed by manipulation of affectors (6), hands, feet, voice; the affectors are controlled by motor centers (7) of the brain. Those centers

Exhibit 5.3C
Expanded Paracognitive Model
(From Norman, 1981)

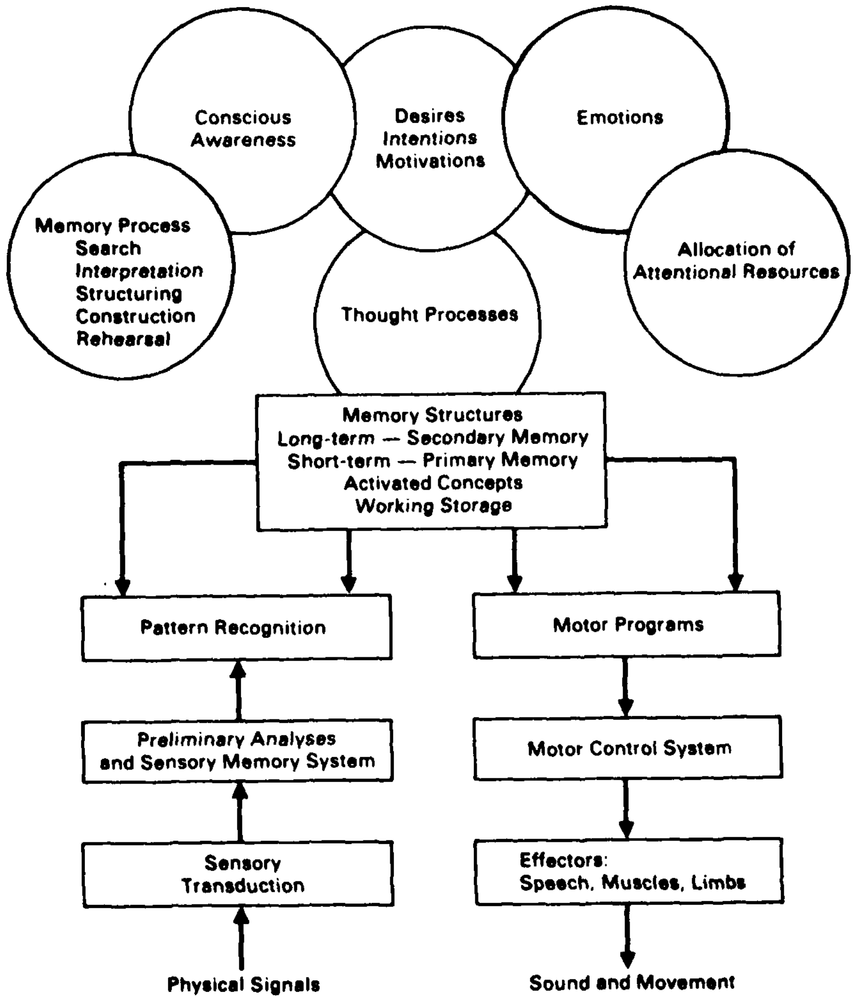
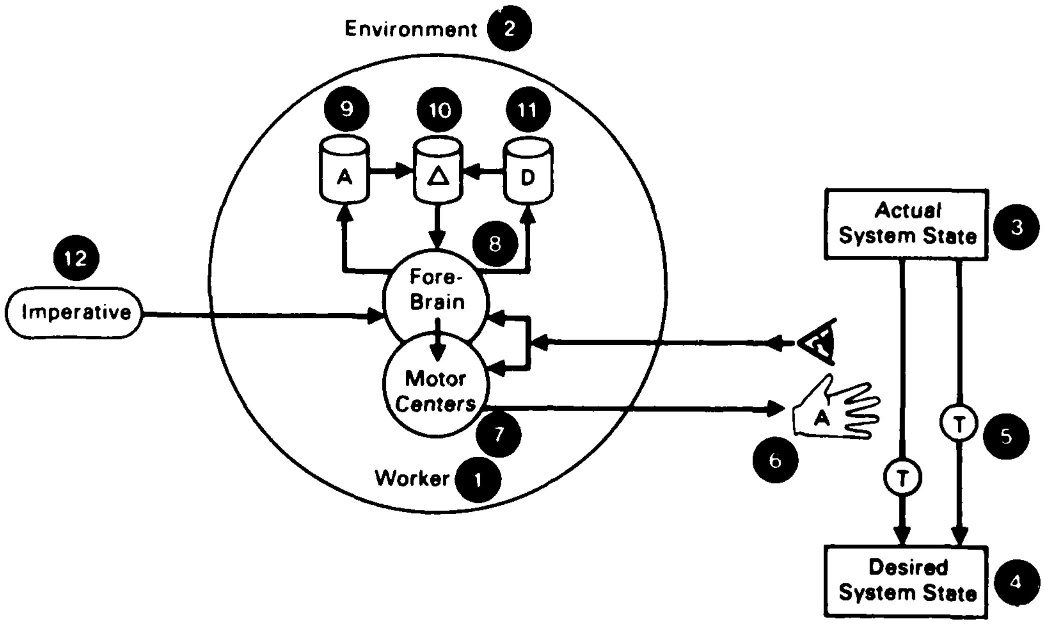


Exhibit 5.3D
The System Delta (From Pulliam, 1981)



are, in turn, controlled by the higher mental activity of the forebrain (8). Maintained in the brain are many overlapping models of the external world. These include a model of the system actual state, as perceived by the worker (9), and a model of the system desired state - the goal to be achieved (10). Finally, there is a model of the difference between the actual and desired states - the system delta (11). The system delta is a mental model of changes - manipulations by which the desired state can be achieved. Obviously these are dynamic models, and are constantly updated by new perceived infomation.

All this activity is driven by an external imperative (12), which dictates the desired system state. This may be altogether external, as in the case of a shop foreman, or may be internalized as when the work product satisfies a need of the worker himself. This model is recommended as the entry model in analyzing highly intellectualized activity such as fault finding, mission planning, and intelligence analysis. Such tasks provide few overt clues to their content since there are few interactions with controls, but they can be analyzed in terms of the sequential contents of the mental models at (9), (10) and (11).

APPENDIX

USES AND HAZARDS OF AUTOMATION

This Appendix provides four lists, suggesting how functions may be appropriately allocated to humans or machines. The first list identifies things which are generally done well by automation, and the second list things generally done well by human beings. The third list identifies things which automation may not do well, and some hazards of allocation to machines. The fourth list identifies things humans may not do well, and hazards of allocation to human beings. List of this kind have been termed "Fitts lists," in recognition of an original list published in 1962 by the late Paul Fitts.

1. Functions Performed Well by Machines and Automation.

1.1 Sensing.

- Machines can sense forms of energy outside the human range.
- Machines can be designed with an arbitrarily low response latency.
- Machine sensors can provide superior sustained reliability.

1.2 Sensory Buffer Storage.

- Automation can provide arbitrarily large, and long-term storage.

1.3 Sensory Channel Capacity.

- Automation can provide effectively unlimited channel capacity - numbers of sensors, sampling rates, bandwidth.

1.4 Signal/Noise Characteristics.

- Automation can provide good filtering of sensor data, to the limits of an ability to specify filtering in terms of spectra or sequential characteristics.
- Automation can recognize and respond to small changes in signal level. It can recognize slowly developing changes, or changes in small increments.
- Automation can be "vigilant" contrasted to humans, in reliably detecting energy or signals.

1.5 Pattern Recognition.

- Automation is reliable for detecting simple, fully predicted (programmed) information patterns.

o Automation is good, fast and accurate at formatting pattern displays for human analysis.

o Automation can be "vigilant" within its pattern-recognition limitations.

1.6 Monitoring.

o Automation is an effective monitor, within its sensing and pattern-recognition limits.

o Automation can provide effective oversight to humans, who are notably fallible in monitoring tasks.

o Automation does not become bored, fall asleep, shift its attention, or become disaffected.

1.7 Information Storage.

o Automation can provide effectively unlimited storage of information. That storage can be reliable and fast.

o Automation can provide unlimited analog data storage, but only at the cost of distortion.

1.8 Information Recall.

o Automation can provide accurate, reliable, high-speed data recall.

1.9 Response (Procedural).

o Automation can respond quickly to control signals (microsecond lag).

o Automation is effective in performing repeated, detailed, precise routine tasks. These tasks must be fully predictable and specifiable as a program sequence.

o Automation can handle a high task bandwidth - many steps at once, high speed procedures, complex tasks. These must be programmable.

o Automation is reliable in procedural tasks, limited only by equipment design, component reliability, and the fact that it is rarely possible to anticipate all the program contingencies.

1.10 Deduction.

o Automation (computing machinery) is outstanding at performing deductive tasks, within the limited range of a programmable algorithm. Artificial intelligence may soon extend that range.

o Automation is quicker and more reliable than humans in recognizing a data set as a member of a class, within a programmable algorithm.

o Automation is appropriate for tasks such as timeline analysis. It can rapidly produce a system optimization, within the programmer's ability to quantify variables and value judgments.

o Automation can reduce human cognitive workload by automatic situation assessment, preplanning strategies, and escape routines.

o Automation can anticipate emergencies.

o Automation can reduce human perceptual and cognitive loads by prioritizing data for display.

o Automation is effective in fault diagnosis, within a programmed paradigm. It has a limited diagnostic repertoire, but performs reliably within that range. Machine diagnoses must be confirmed by humans.

1.11 Induction.

(No practical capability for automatic induction has been shown.)

1.12 Computation.

o Machines calculate more rapidly and reliably than humans, except that input-output rates for some computations may be higher for humans.

o Automation is efficient in scheduling, resource allocation.

o Automation provides the speed of computation required for tasks such as weapons delivery and fire control.

o Automation is ideal as a tool for computing navigation and controlling communications.

o Automation can reduce human cognitive and perceptual workload by integration of data for displays.

o Automation can improve human control performance by providing predictive and quickened (feedback) displays.

1.13 "Judgment."

(The term "judgment" resists definition but requires the interaction of value with memory and deductive logic. Machines do not as yet provide anything resembling judgment, but with advances in artificial intelligence will probably do so.)

1.14 Responsibility.

(By its definition, responsibility must be assigned to a human.)

1.15 Power and Force.

o Machines can exert large forces smoothly and precisely.

o Machines can provide power limited only by design and cost.

o Machines can exert small forces more precisely than humans, although in certain complex cases human control of small forces is more precisely applied.

1.16 Manipulation.

o Machines can manipulate their own integral parts with high speed, reliability and precision.

o Machines have a limited capability to grasp objects. Within that capability, they perform more reliably than humans, but not in all cases more precisely.

o Automatic speed of manipulation is good in simple routines.

o Automation is an effective means of manipulating flight trajectory and attitude controls.

o Automation is effective in engine and power control.

o Automation can perform manipulations continuously for long periods of time.

o Automation can perform tracking tasks at relatively high and low speeds, but within human bandwidths, humans track more flexibly, and adapt more effectively to complex tracking paths.

1.17 Sensitivity - Informational.

o Machines are not perturbed by human emotional and situational problems. They do not fall in love, or suffer loss of morale.

o Automation is appropriate, within programmability, to perform long duration missions where humans would suffer from isolation, sensory or perceptual deprivation.

o Automation is appropriate for tasks which humans find distasteful.

o Automation is appropriate for tasks in which humans suffer from fatigue, or informational overload.

1.18 Sensitivity - Physical

o Machines can be designed to withstand large dynamic forces.

o Machines can be designed to resist conditions hazardous to man, such as radiation, extremes of temperature, reduced gravity, toxic environments.

o Machines can be designed to degrade very slowly in time, and to provide sustained performance in spite of wear and physical accident.

o Machines are appropriate to replace humans in hazardous military missions, hostile exploratory environments, hostile industrial environments, and in restricted physical spaces.

1.19 Economics.

o Machines or automation can replace most human functions, given development funding, professional talent, and time. All of these are severely limited resources.

o Machines can be economically developed when a large number of units will replace a large number of human functions. Even where machines are much more effective, human performance may be more economic if only a few cases are involved.

o Automation can be especially cost efficient in aircraft and in space missions, where the human costs of body weight and of life support equipment are high.

o Machines can be expendable.

2. Functions Performed Well by Human Beings.

2.1 Sensing.

o Humans have several sensory systems, which can detect a wide variety of stimuli. Several of them (vision, hearing and touch) are more sensitive than any available mechanical sensor, except for a few devices of narrow bandwidth.

o Human senses are highly controlled. Vision is capable of very rapid fixation, and hearing has an equivalent practical capability.

o Human senses are capable of discriminating meaningful signals in the presence of noise, and of rapid, subtle pattern recognition.

o At the sensory level, humans have a very high bandwidth, and an ability to sample that range selectively for meaningful information. That capability is limited by processing bandwidth.

2.2 Sensory Buffer.

o Human sensory data are held in the equivalent of buffer storage for a second or so. During this time the data decay, but are available for reevaluation by conscious and subconscious processes of the nervous system. These data are used to select data for further processing, and to control the continued focus of attention.

o Contents of the sensory buffers are high for vision and hearing, but are limited for smell, touch, temperature, taste, balance, kinesthetics and pain.

o Contents of sensory buffers are highly focused, with fine detail at points of fixation and diminishing detail for peripheral data. Contents are highly dependent on the direction of attention. Humans should be used as sensors under conditions which assist the focus of attention prior to critical events. This focus can be provided by automatic alarms.

2.3 Sensory Channel Capacity and Sensory Processing.

o Sensory processing provides an ability to integrate sensory data, without conscious intervention, against a single target. Thus a surface is perceived as "rough" due to integrated visual and tactile data.

o Humans should be used with automated sensing and storage aids, for tasks which require brief periods of high perceptual demand.

2.4 Signal/Noise Characteristics.

o In general, human senses are superior to existing automation in discriminating meaningful signals in the presence of noise. They should be assisted by the specialized capabilities of automation, which can provide prior spectral and formula-based filtering.

2.5 Pattern Recognition.

o Humans are superior to existing machines in recognizing patterns, especially in the presence of interference. They can recognize spatial patterns, spectral patterns in sound, and temporal patterns in events.

o Humans can use pattern recognition to simplify complex input data, by formulating meaningful "wholes."

o Humans can recognize patterns in spite of changes in size, orientation, rotation, or distortion.

o Humans can learn to distinguish patterns in displays - patterns of lights, correlations in indicators, sequences of indicator events. This capability is unreliable, and should be assisted by automated integration of data, or automated alarms, when feasible.

o Humans have a capability for "perceptual filling," which enables them to identify a whole pattern from a few cues, when most of the data are obscured. Thus a hunter "sees" a squirrel among the leaves by a glimpse of its tail. This capability can lead to error or illusion, especially when the observer has a bias or prior expectation.

2.6 Monitoring.

o Humans are effective monitors for brief periods, to identify complex events given proper training, and given an alerting signal.

o Humans should be used for monitoring tasks with automated support.

o Humans should be used with an artificially active routine, to ensure their systematic attention and active analysis of displayed data.

o Incorporate automated alarms where possible. Do not permit a condition where multiple alarms may confuse the operator.

o Provide ground communications support to critical airborne monitor requirements.

2.7 Information Storage.

o Humans have the general ability to store large amounts of information, and to recall pertinent information rapidly. This ability is limited by the structure of memory, which includes a long-term memory (LTM) and a short-term memory (STM), with different characteristics.

o Read-in channel capacity to memory is limited by the capacity of STM, which can attend to only about 1.5 sensory channels, and hold about 5 - 7 significant data at one time. Those data fade rapidly, and are replaced with new experience data, unless reinforced by rehearsal or active task performance.

o Data from STM may be stored in LTM, depending on their perceived importance, their active use, and the presence or absence of interfering experience.

o When experiential or display data appear rapidly, humans are unable to retain those data in STM and use them to formulate a response. Use humans in tasks which have momentary high data input rates by providing buffer data displays, or buffer memory available on command.

o Human memory for patterns, strategies, principles, and contingencies of action is superior to that of a machine. This memory depends on the linkage of what is remembered to prior experience, and to the perceived needs of the observer.

o Humans can remember analog sensory data which form meaningful patterns, with a high fineness of relative scale (frequencies, positional data).

2.8 Information Recall.

o Human memory is unique in providing storage based on a hierarchy of importance. As a result, data perceived as important are readily recalled, and other data are recalled more slowly and less reliably.

o For completely random recall, human memory is superior. For planned data retrievals, and compared to machines, human recall is slower, less reliable, and situation-dependent. Machines are better only when the data addresses have been identified, and the data placed in an addressable register.

2.9 Response (Procedural).

o Humans can exercise a wide repertoire of learned procedural responses, and can adjust or modify those responses to meet contingencies. Response repertoire is limited by learning rates; reliability may be low compared to machines.

o Pilots or operators should be supported with simulators to maintain a repertoire of required psychomotor responses. Build simulators into operational equipment (embedded training) to maintain repertoires of psychomotor skills.

2.10 Deduction.

o Humans have an advantage in flexibility and universality in deduction. However they are generally inferior to machines because of limited speed, parallel capacity, and reliability.

o Humans are able to learn adaptively and to profit deductively from prior experience, including very recent task events.

o Humans are able to handle deduction for low probability events, which cannot be economically programmed into a machine.

o Humans are flexible and can, in effect, change their own deductive programming when necessary.

o Humans can consider and evaluate a wide range of alternatives, drawing on their flexible and value-based memory store. They can formulate alternatives which were not foreseeable at the time of system design.

o Humans can develop new deductive responses. In case of failure, they can reconfigure a system, or invent a new escape strategy.

o Humans can accomplish similar objectives by alternate means, or if an original objective is not achievable, they can formulate alternate objectives.

o Human deduction is adaptable but fallible. For tasks where errors in deduction may be serious, provide ground communication support. Consider developing artifical intelligence routines to evaluate and verify human decisions.

o Human deduction provides the best full-range solution to fault diagnosis or trouble-shooting. Human fault diagnosis is slow, and may not follow optimal logical pathways. Support human trouble-shooting with built-in tests, and with automated diagnostic procedures.

2.11 Induction.

o To this date, humans alone can perform inductive reasoning. This makes it possible for humans to generalize from a few data, and to generate completely new solutions not derivable by deductive logic.

o Humans can explore and experiment, both actively and as a mental process. This may lead to both good and bad reponses. Design systems so that the human tendency to explore cannot lead to damage or failure.

o Inductive logic can lead to rapid, intuitive successes in diagnosis.

o Humans are able to solve problems by heuristic strategies.

o Humans are able to generate classes of events, and recognize members of a class.

2.12 Computation.

o Humans have an occasional advantage in input-output speed. For simple computations, they can perceive quantities, compute an answer, and take action more rapidly than the data can be read to and from a machine.

o Humans are better than machines at analyzing and evaluating geometrical relationships.

o Humans are much better than machines at recognizing and correcting errors.

2.13 "Judgment."

o Humans are capable of exercising combinations of inductive logic, deductive logic, and memory to relate action to values. This requires the evaluation of conceptual and other data not quantifiable, and is a function which to this date cannot be performed by machines. Use humans where judgmental decisions are required.

2.14 Responsibility.

o Humans are ultimately responsible for how a system is employed, and for the consequences of system failure. Identify the points in a system where command decisions are required, or where responsibility must be exercised. Use automation to ensure that information is displayed to the person responsible. Ensure that the system is designed so that the responsible person can in fact intervene and exercise control. Ensure that critical historic data are collected and preserved.

2.15 Power and Force.

o Use humans to provide power or force when the required action is momentary, within human capability, and when use of humans is more economical.

o Use humans to provide finely modulated, low levels of power or force.

2.16 Manipulation.

o Humans have a flexible ability to grasp and manipulate objects, within a narrow range of power and speed. Within that range they are generally superior to machines.

o Humans can perform fine manipulations required in assembly tasks, soldering, calibration, and adjustment.

o Humans can perform manipulations in a non-programmable routine, and with rapid feedback from the senses.

o Humans can perform complex tracking tasks. Although machines are superior in high-speed, multichannel and continuous tracking, humans can track more finely, more adaptively, and with flexible tracking stragegies.

o Human tracking is less dependable than that of a machine, and cannot continue over long periods of time.

2.17 Sensitivity - Informational.

o Humans can operate for short periods under a variety of unpredictable overloads and information noise. This capability is motivation dependent.

o Humans can adjust to overload by reducing their processing rate, under conditions which would cause an automated system to fail.

o Humans are able to effectively filter meaningful data from noise (see 2.4).

o This capability varies with individuals. Select humans in critical jobs by testing for performance under stress, threat and informational overload.

2.18 Sensitivity - Physical.

o Humans can handle a wide range of temporary physical stresses and overloads, within a limited range. Use humans where these stresses are occasional, and where human performance is the least expensive choice.

2.19 Economics.

o In general, humans are a high-cost component. Trained people are expensive. They require elaborate work facilities, organizational support, and overhead costs. Use automation when it will reduce the cost of task performance.

o Use humans where a limited number of units will be required, and where the costs of developing automation are therefore not justified.

o Use humans where automation is not feasible, at the current state of technology.

o Use humans for utilitarian functions (see subsection 4.3).

3. Limitations and Hazards of Automatic Performance.

3.1 Sensing.

o Machine sensors have poor signal detection in the presence of noise. When noise spectra overlap, they are subject to false detection or to failure to detect. They are easy to jam.

o Machine sensor systems are relatively insensitive to direction, slow and awkward to orient in direction.

o Machine sensors can provide lower detection thresholds than human sensors, but these are in general narrow-band and high-cost devices.

3.2 Sensory Buffer Storage.

o Machine buffer storage has effectively unlimited capacity, but is unable to address collected data meaningfully, unable to assign priority to data, and unable to purge noise from meaningful data.

3.3 Sensory Channel Capacity and Processing.

o Automated sensory channel capacity can be arbitrarily large, at a cost.

o Automated processing has only limited capacity to redirect data collection in response to data content or value.

3.4 Signal to Noise Characteristics.

o Electronic filters can provide superior noise discrimination, but only where noise can be specified in terms of discrete spectra.

3.5 Pattern Recognition.

o Automated systems have a limited capacity to recognize meaningful patterns, and are reliable within that range. They recognize only preprogrammable and non-subtle discriminations. Humans should be included in an automated system where patterns must be detected.

3.6 Monitoring.

o Automation provides reliable monitoring, but this capability is limited by the ability of machines to detect patterns and meaning. An automatic monitor can detect only preprogrammed contingencies.

3.7 Information Storage.

o Automatic storage is "dumb" storage. It stores every datum encountered. It cannot prioritize data, cannot distinguish data from noise, cannot assign meaningful addresses to data except addresses based on time and data channel.

o Automation does not store data economically without human intervention.

o Automation cannot store analog data without distortion.

3.8 Information Recall.

o Automated recall is inefficient because of the lack of an optimal addressing structure. For many applications humans should be present in the loop to evaluate and readdress recalled data.

3.9 Response (Procedural).

o Automation is difficult and expensive to program. Usually it is not possible to program for all possible contingencies, both because of the costs of programming, and because the contingencies cannot be anticipated.

o Automatic programs can remain full of bugs - "surprises" - long after they are believed perfect.

o Automated responses are relatively inflexible. Flexibility can be achieved only at high cost.

3.10 Deduction.

o To achieve a complexity equal to that of a human would require massive computers, unreasonable costs and development times.

o The cost of maintenance rises with capability.

o Deductive ability is limited by inability to perceive organization in data. A limited capacity to detect organization is achieved only with large machines, elaborate programming, and difficult prior analysis.

3.11 Induction.

(No applied inductive capability has been demonstrated for automation.)

3.12 Computation.

o Machines have poor capability to detect errors in operation or in procedure.

o Machines have poor capability to correct errors when detected.

o Errors in machine computation may cascade into total process failure.

3.13 "Judgment".

(Machines cannot exercise anything resembling judgment.)

3.14 Responsibility.

(Responsibility cannot be assumed by a machine.)

3.15 Power and Force.

o Within the middle range of human capability, humans can modulate power and force more finely than machines.

3.16 Manipulation.

o To date, machines have limited capability to grasp objects.

o For some applications within the human range, humans can manipulate more precisely, and human sensor-to-affector feedback is superior.

o Within the human range, humans can track single targets more precisely and adjust more quickly to changes in behavior of the target being tracked.

3.17 Sensitivity - Informational.

o Machine logic is vulnerable to disruption by noise in the input signals.

o Input overloads may lead to failure.

o Resistance to informational overload, jamming and noise is achieved only at a high programming cost.

3.18 Sensitivity - Physical.

o Machines are vulnerable to minor damage. They break down completely when single components fail. They do not "heal."

3.19 Economics.

o Automation of all but the simplest functions is achieved only at high dollar cost, a high cost in development time, and by diverting limited engineering talent to the problem concerned.

o Automation typically cannot be afforded to replace humans unless many people are replaced for an extended time.

4. Limitations and Hazards of Human Performance.

4.1 Sensing.

o Human senses have a relatively high response latency.

o The effectiveness of human senses is reduced by fatigue.

o Human senses are damaged by signal overloads.

4.2 Sensory Buffer Storage.

o Information detected by human sensors is available for only a few seconds at most. If not picked up in short-term memory (STM), it is lost.

4.3 Sensory Channel Capacity.

o Compared to machines, humans have very limited sensory channel capacity.

o Human attention is highly focused. Very limited information is collected outside the point of focus.

o Humans cannot effectively share attention. They tend to fix on one signal or problem, and disregard others of equal or greater value.

4.4 Sensory Processing and Signal/Noise Characteristics.

o The ability to perceive meaningful information in sensory data is limited by experience and training.

o Human ability to "fill" patterns can lead to false perceptions.

o Humans tend to fulfill expectations in perception, regardless of the data input.

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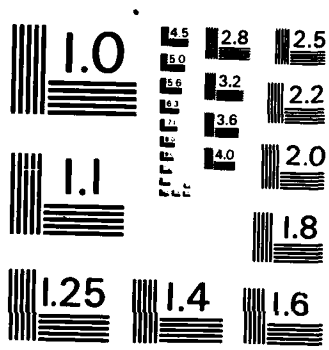

MICROCOPY RESOLUTION TEST CHART
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4.5 Pattern Recognition.

o Human pattern recognition in the presence of noise decays rapidly with fatigue, or high levels of demand.

o Human pattern recognition fails when the interfering noise is meaningful.

o Humans recognize distance, speed and clearance by pattern recognition, but their performance is inferior to that of automation. Humans underestimate greater distances. Estimation of distance and speed is perturbed by conditions such as haze.

4.6 Monitoring.

o Humans are notably poor monitors, and should not perform monitoring tasks for more than a few minutes without automated support.

o Human monitoring is further impaired when there are a large numbers of displays, information inputs, or critical events to be detected.

o Humans typically think about other things in a monitoring situation. They cannot avoid this tendency. There is no training or motivational fix.

o Humans tend to become complacent during periods of no alarm.

o Humans cannot respond to more than one alarm signal effectively.

o Humans are subject to initiating false alarms.

4.7 Information Storage.

o Human STM has limited capacity and a fast decay rate. It is a severely limiting factor in human channel capacity.

o Human long-term memory is unreliable.

4.8 Information Recall.

o Human recall is unreliable, and varies with time and circumstances.

4.9 Response - Procedural.

o Human procedural responses are single-channel.

o Under stress, humans revert to prior behavior patterns in preference to recently learned procedures.

o Under stress, humans revert to simpler and more intuitive behaviors, in preference to learned procedures.

o Humans will not read procedures if they think they remember them.

o Humans will not recheck their performance of a procedure.

4.10 <u>Deduction</u>.

o Human deduction is a single-channel process.

o Human deduction is very slow compared to machine logic.

o Human deduction is perturbed by emotion, prior opinion, personal interests, stress.

o Human deduction is not reliable, and reaches differing conclusions on sequential tries.

o Humans tend to underestimate or disregard hazards, although deductively aware of probable consequences.

o Humans tend to persist in error behaviors after they are deductively aware of the error.

4.11 <u>Induction</u>.

o Humans cannot exercise inductive logic on demand.

4.12 <u>Computation</u>.

o Human computation is slow, inaccurate and unreliable.

o Human judgments concerning optimal strategy - game theoretic or decision theoretic estimates - are subject to intuitive errors.

o Human estimates or mental computation of statistical conditions are subject to systematic errors. Humans overvalue recent data and events. They evaluate data using subjective criteria. They undervalue the severity of an emergency once it is detected.

4.13 <u>"Judgment."</u>

o Humans may be unable to exercise judgment when circumstances do not provide a feeling of confidence.

4.14 <u>Responsibility</u>.

o Humans may seek to evade responsibility.

4.15 <u>Power and Force</u>.

o Humans can generate only limited power and force, for limited periods of time.

4.16 Manipulation.

o Human manipulation cannot be standardized from trial to trial.

o The precision of human manipulation degrades at high power and force loadings.

o Human manipulation degrades rapidly with fatigue or time.

o Human manipulation depends on sensory feedback, and is impaired if sensor function is obstructed. It is impaired when other meaningful signals are being received.

o Human manipulation is degraded by heat or cold.

o Human manipulation is a single channel capability. It is bandwidth limited to about two control or adjust operations per second.

o Human manipulation has a relatively high response latency.

o Manipulative performance may degrade with time due to boredom, distraction, loss of motivation.

4.17 Sensitivity - Informational.

o Human performance is vulnerable to distracting signals.

o Human performance degrades sharply when information loads exceed capacity. Humans become "confused," or experience panic.

o Humans are vulnerable to a wide range of emotional and other affective conditions.

4.18 Sensitivity - Physical.

o Humans can tolerate only limited levels of imposed force.

o Humans are vulnerable to a wide range of environmental hazards.

4.19 Economics.

o Human performance is uneconomical for any task which can be clearly proceduralized, and which will be performed a sufficient number of times to justify an automated solution.

o Human costs are typically underestimated by designers. Real hourly rates must be adjusted by a typical 150% overhead. Be sure to consider costs of training, organizational support, recruitment, lost time, retirement and fringe benefits.

o Where highly skilled or high ability people are required, the impact of diverting those people from other jobs must be considered.

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